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Basics of Pump-and-Treat Ground-Water Remediation Technology

GeoTrans, Inc., Herndon, VA

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16. ABSTRACT

The pump-and-treat process, whereby contaminated ground water is pumped to the surface for treatment, is one of the most common ground-water remediation technologies used at hazardous waste sites. However, recent research has identified complex chemical and physical interactions between contaminants and the subsurface media which may impose limitations on the extraction part of the process. This report was developed to summarize the basic considerations necessary to determine when, where, and how pump-and-treat technology can be used effectively to remediate ground-water contamination.

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Foreword

EPA is charged by Congress to protect the nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the Laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and the subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil, and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to soil and subsurface environment, for the protection of this resource.

The pump-and-treat process, whereby contaminated ground water is pumped to the surface for treatment, is one of the most common ground-water remediation technologies used at hazardous waste sites. However, recent research has identified complex chemical and physical interactions between contaminants and the subsurface media which may impose limitations on the extraction part of the process. This report was developed to summarize the basic considerations necessary to determine when, where, and how pump-and-treat technology can be used effectively to remediate ground-water contamination.

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Introduction

Purpose of report

A common means to contain and/or remediate contaminated ground water is extracting the water and treating it at the surface, which is referred to as pump-and-treat technology. This report provides basic guidance on how to use available hydrogeological and chemical data to determine when, where, and how pump-and-treat technology can be used successfully to contain and/or remediate contaminant plumes. Ways to estimate the time required to achieve a specific ground-water cleanup goal also are discussed. Finally, the report addresses practical limitations of pump-and-treat technology given certain combinations of hydrogeological conditions and geochemical properties. This report emphasizes the "pump" portion of pump-and-treat technology. Estimated discharge rates and concentration loadings will affect the aboveground treatment and associated costs. Treatment strategies and policy questions are not discussed but can be found in U.S. EPA (1987a) and U.S. EPA (1988a).

Pump-and-treat technology generally is considered at hazardous waste sites where significant levels of ground-water contamination exist. The report is written for persons considering pump-and-treat technology as a remedial alternative to contain and/or clean up a ground-water contaminant plume. It is assumed that the reader has some familiarity with basic concepts of hydrogeology.

Format of report

The report is divided into four main sections: (1) Overview, (2) Data Requirements, (3) Conceptual Design, and (4) Operation and Monitoring. Examples and illustrations are provided to convey concepts. In addition, a glossary enables the reader to review the meaning of technical terms introduced in the text. The first occurrence of terms listed in the glossary is indicated by **bold type**. Because this report only provides basic information and concepts on pump-and-treat technology, references are provided for more detailed information.

The first section provides an Overview of pump-and-treat technology. Data Requirements identifies the hydrogeological and contaminant data needed for chemical transport analysis. Included are discussions of data collection methods, data interpretation, and handling data uncertainties.

Pump-and-treat technology for containment and cleanup is discussed in Conceptual Design. Favorable and unfavorable conditions for using a pump-and-treat system are outlined. A discussion of chemical and hydrogeological properties that affect the appropriateness of pump-and-treat technology is presented. Methods to determine well spacings, pumping rates, and cleanup time also are discussed. Examples illustrate which contaminants and hydrogeological environments can be treated successfully with pump-and-treat technology and those for which pump-and-treat systems need to be supplemented with other remedial technologies.

The final section, Operation and Monitoring, emphasizes the need for setting **remedial action objectives** and for monitoring to ensure that these goals are attained. Once the pump-and-treat system is implemented, adjustments and modifications invariably will be required. Ways to evaluate the pump-and-treat system are discussed along with typical modifications.

Appendices provide (1) data on various chemicals that are relevant to pump-and-treat systems and (2) a summary of observations at sites where pump-and-treat technology has been, or is presently being, used.

Overview

Sources of ground-water contamination can range from leaky tanks, landfills, and spills, to the less obvious, such as chemicals in the soil dissolving from nonaqueous phase liquids (**NAPLs**) or chemicals desorbing from the soil matrix. Several options can be used to attempt containment and/or cleanup of ground-water contamination. First, however, a distinction needs to be made between source removal and the actual ground-water cleanup. Source removal typically refers to excavation and removal of wastes and/or contaminated soil. It also can include **vacuum extraction**. Source containment includes chemical **fixation** or physical encapsulation; if effective, it is similar to source removal in that it eliminates the potential for continued chemical transport from the waste source to ground water. Ground-water containment/cleanup options include physical containment (e.g., construction of low-permeability walls and covers), in situ treatment (e.g., bioreclamation), and hydraulic containment/ cleanup (e.g., **extraction wells** and intercept trenches/drains). To effect complete cleanup, several methods may be combined to form a **treatment train**. This report focuses only on hydraulic containment/ cleanup, in particular, pump-and-treat technology.

In a pump-and-treat system used for cleanup, contaminated ground water or mobile NAPLs are captured and pumped to the surface for treatment. This requires locating the ground-water contaminant plume or NAPLs in three-dimensional space, determining **aquifer** and chemical properties, designing a capture system, and installing extraction (and in some cases injection) wells. **Monitoring wells/piezometers** used to check the effectiveness of the pump-and-treat system are an integral component of the system. Injection wells are used to enhance the extraction system by flushing contaminants (including some in the **vadose zone**) toward extraction wells or drains. A pump-and-treat system may be used in combination with other remedial actions, such as low-permeability walls to limit the amount of clean water flowing to the extraction wells, thus reducing the volume of water to be treated.

Figure 1 shows a pump-and-treat system operating at a landfill in a typical hydrologic setting. In this case, an injection well is used to increase the **hydraulic gradient** to the extraction wells. This can increase the efficiency of the extraction wells, reducing the time required to reach a cleanup goal.

Pump-and-treat technology also can be used as a **hydraulic barrier** to prevent off-site migration of contaminant plumes from landfills or residual NAPLs. The basic principle of a barrier well system is to lower groundwater levels near a line of wells, thus diverting groundwater flow toward the pumping wells.

Whether the objective of the pump-and-treat system is to reduce concentrations of contaminants to an acceptable level (cleanup), or to protect the subsurface from further contamination (containment), the system components are:

- a set of goals or objectives,
- engineered components such as wells, pumps and a treatment facility,
- operational rules and monitoring, and
- termination criteria.

Each of these components must be addressed in the design and evaluation of a pump-and-treat technology.

Pump-and-treat technology is appropriate for many groundwater contamination problems (Ziegler, 1989). The physical-chemical subsurface system must allow the contaminants to flow to the extraction wells. Consequently, the subsurface must have sufficient **hydraulic conductivity** (K) to allow fluid to flow readily and the chemicals must be transportable by the fluid, thus making the use of pump-and-treat systems highly site specific.

Cases in which contaminants cannot readily flow to pumping wells include:

- **Heterogeneous** aquifer conditions where low-permeability zones restrict contaminant flow toward extraction wells;
- Chemicals that are sorbed or precipitated on the soil and slowly desorb or dissolve back into the ground water as chemical equilibrium changes in response to the extraction process; or
- Immobile nonaqueous phase liquids (NAPLs) that may contribute to a **miscible** contaminant plume by prolonged dissolution (e.g., a separate phase gasoline at **residual saturation**).

In these cases, modifications to pump-and-treat technology, such as **pulsed pumping**, may be appropriate. Pump-and-

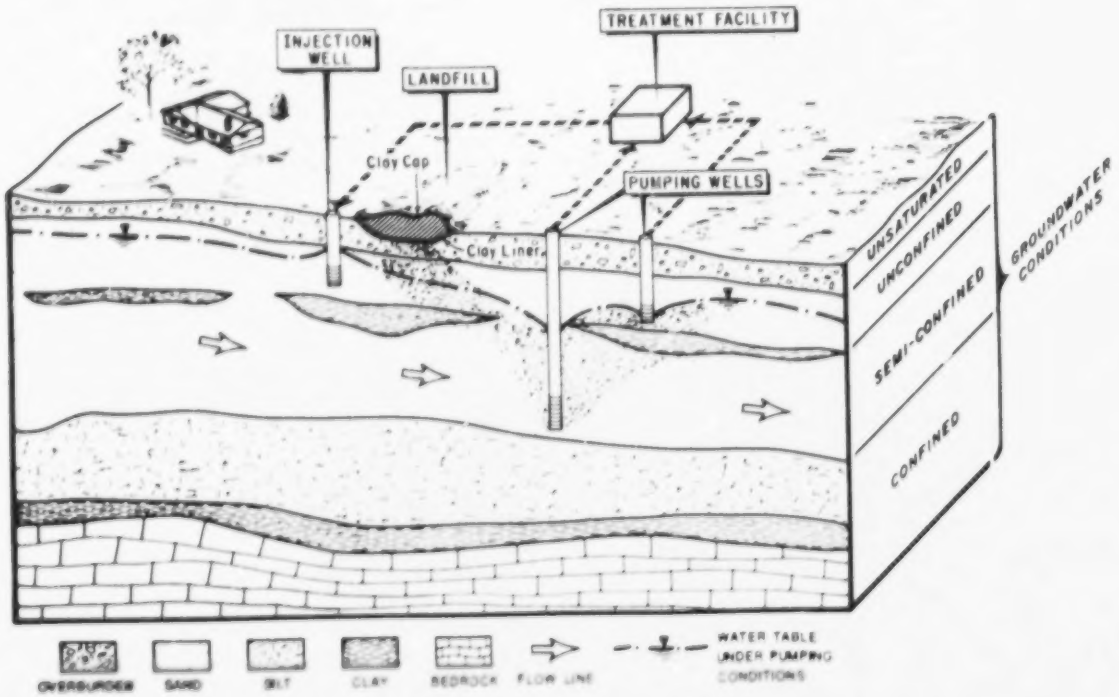

Figure 1. Example setting where a pump-and-treat system is used.

treat technology also may be used in combination (treatment train) with other remedial alternatives, such as vacuum extraction and/or bioremediation. One should realize that no single technology is a panacea for subsurface remediation under complex conditions.

The main limitation of pump-and-treat technology is the long time that may be required to achieve an acceptable level of cleanup. Other potential limitations include: (1) a design that fails to contain the contaminant plume and allows continued migration of contaminants either horizontally or vertically and (2) operational failures that allow the loss of containment. Typical operational problems stem from the failure(s) of surface equipment, electrical and mechanical control systems, and chemical precipitation causing plugging of wells, pumps, and surface plumbing. Limitations are discussed further in Mackay and Cherry (1989).

The problem of site remediation is complicated further if the contaminants occur as NAPLs such as gasoline, heating oil or jet fuel. In this case, some of the oily phase becomes trapped in pore spaces by capillary forces and cannot readily be pumped out. This residual saturation can be a significant source of miscible contamination. Unfortunately, the residual NAPL may not be detected by a monitoring well because only the dissolved fraction is present in the water withdrawn. Pump-and-treat removal is rate-limited by how fast the NAPL components can dissolve. Thus, for this situation, pump-and-treat removal may need to be combined with other remedial alternatives (e.g., vacuum extraction) that better address residual saturation; and/or hydraulic containment rather than cleanup may be the realistic remedial objective.

Data Requirements

A conceptual model of the nature and scope of a ground-water contamination problem is needed before an appropriate remedial action can be determined. Data collection should be an iterative process performed in phases where decisions concerning subsequent phases are based on the results of preceding phases. This phased approach need not lead to data collection being a discontinuous process; data may well be collected continuously with the decision resulting in modifications in collection protocols. These decisions should consider which final and/or interim remedial actions are to be implemented. A history of the contamination events should be prepared to define the types of waste and quantify their loadings to the system. This is necessary to help design the data collection program. The minimum data required to make informed decisions depends on the processes controlling contamination. These processes and associated data are discussed below.

Hydrogeological data

One of the key elements affecting pump-and-treat system design is the characterization of the ground-water flow system. This includes: the physical parameters of the contaminated region (e.g., hydraulic conductivity, **storage coefficient**, and aquifer thickness); system stresses (e.g., recharge and pumping rates); and other system characteristics (e.g., physical and hydraulic boundaries and ground-water flow directions and rates). For long-term pumping, the storage coefficient is less significant than the hydraulic conductivity. By understanding where ground water recharges and discharges (mass balance), the laws governing flow (e.g., **Darcy's Law**), and the geological framework through which this flow occurs, it is possible to determine these characteristics. It is important to portray the flow system accurately so the impact of installing a pumping system can be properly analyzed. Table 1 lists the information typically used to identify and quantify the important characteristics of a ground-water system. The methods for collecting these data are discussed in a later section.

Because migrating miscible contaminants travel with moving ground water, it is important to characterize ground-water flow. Ground water flows from areas of recharge (commonly via rainfall, surface water bodies, or irrigation) to areas of discharge (surface water or wells). Along the way, subsurface heterogeneities (such as fractures) influence its direction. The rate of ground-water flow is controlled by the **porosity** and hydraulic conductivity of the media through which it travels and by hydraulic gradients, which are influenced by recharge and discharge (see Freeze and Cherry, 1979 or Fetter, 1980).

Pumping wells influence the flow system. If contamination is detected in a water supply well, there has been a tendency to close the well. This alters the flow system and causes the contaminant's plume to migrate elsewhere. Depending on the site, it may be advantageous to install well-head treatment and keep the well on-line to prevent further plume migration. Conversely, it may be advantageous to close the well if it is believed further pumping might exacerbate spreading of the plume. This interim remedial action may be consistent with and can become part of a final pump-and-treat system.

It is important to conduct a site characterization quickly; however, ground-water flow systems vary with time. Seasonal variations in water levels, which are often several feet, can adversely impact remediation. For example, at one site, an intercept drain was constructed to collect contaminated ground water but was designed based on only one survey of water levels. Subsequent monitoring revealed that the water levels represented a seasonal high. Thus, for most of the year, the ground-water intercept drain was above the water table and did not collect the contaminated ground water.

Table 1. Aspects of Site Hydrogeology (U.S. EPA, 1988).

Geologic Aspects

1. Type of water-bearing unit or aquifer (overburden, bedrock).
2. Thickness, areal extent of water-bearing units and aquifers.
3. Type of porosity (primary, such as intergranular pore space, or secondary, such as bedrock discontinuities, e.g., fracture or solution cavities).
4. Presence or absence of impermeable units or confining layers.
5. Depths to **water table**; thickness of vadose zone.

Hydraulic Aspects

1. Hydraulic properties of water-bearing unit or aquifer (hydraulic conductivity, transmissivity, storativity, porosity, dispersivity).
2. Pressure conditions (confined, unconfined, leaky confined).
3. Ground-water flow directions (hydraulic gradients, both horizontal and vertical), volumes (specific discharge), rate (average linear velocity).
4. Recharge and discharge areas.
5. Ground-water or surface water interactions; areas of ground-water discharge to surface water.
6. Seasonal variations of ground-water conditions.

Ground-Water Use Aspects

1. Existing or potential underground sources of drinking water.
2. Existing or near-site use of ground water.

Contaminant data

Contaminant information includes: (1) source characterization, (2) concentration distribution of contamination and naturally occurring chemicals, and (3) data associated with the processes that affect plume development. Source characterization consists of the following: (1) the chemical volume released, (2) the area infiltrated, and (3) the time duration of release. Often, the release occurred so long ago that information is difficult to obtain.

Chemical data

Quantitative characterization of the subsurface chemistry includes sampling the vadose and saturated zones to determine the concentration distributions in ground water, soil, and vadose water. Vadose zone monitoring is discussed in Wilson (1981, 1982, 1983). A network of monitoring wells (also necessary for the hydrogeologic data) needs to be installed to collect depth-discrete ground-water samples (U.S. EPA, 1986a). Wells should be located in areas that will supply information on ambient (background) ground-water chemistry and on plume chemistry. At a minimum, soil and ground-water samples should be analyzed for the parameters of concern from the waste stream. A full priority pollutant scan on the first round provides information on plume chemistry and may be useful in differentiating plumes that have originated from a different source. On subsequent rounds, the parameter list may be tailored based on site-specific considerations. For example, the list may include chemicals exceeding environmental regulations and those causing important chemical reactions that affect the mobility of the contaminant or the pump-and-treat system (e.g., compounds producing iron precipitation in the surface plumbing due to oxidation).

After analyzing the samples, the resulting concentration data should be mapped in three dimensions to determine the spatial distribution of contamination. These plume delineation maps and the results from **aquifer tests** will yield estimates on plume movement and identify locations for extraction wells.

Solute transport data

Plume movement of nonreactive dissolved contaminants in saturated porous media is controlled primarily by **advection** and, to a lesser extent, hydrodynamic **dispersion** (Figure 2). Advection is a function of hydraulic conductivity (the soil's resistance to flow) times the hydraulic gradient (water-level changes with distance) divided by porosity. Hydrodynamic dispersion is the combined effect of mechanical mixing and molecular **diffusion**. It is the apparent mixing due to unresolved advective movement at scales finer than those described by mean advection. Dispersion causes the

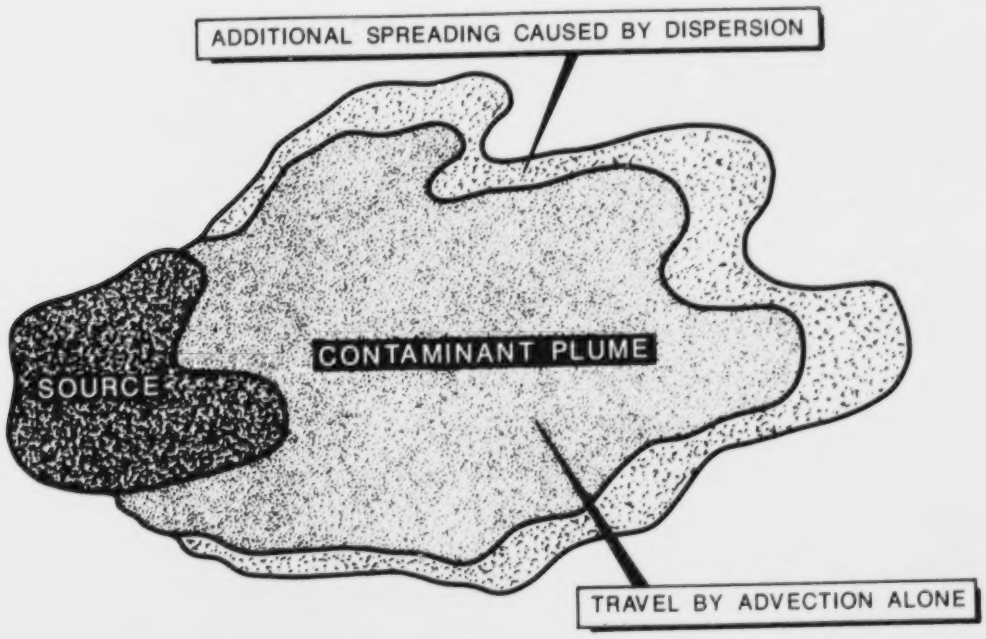

Figure 2. Plan view of contaminant plume spreading by advection and dispersion (from Keely, 1989).

zone of contaminated ground water to occupy a greater volume than it would under advection only. Advection causes a plume to move in the direction and at the rate of ground-water flow; hydrodynamic dispersion causes the plume volume to increase and its maximum concentration to decrease.

Transport of reactive contaminants is influenced by additional processes such as **sorption**, **desorption**, and chemical or biochemical reactions. The data requirements for contamination characterization are presented in Table 2. Sorption-desorption and transformation processes are important in controlling the migration rate and concentration distributions. Some of these processes tend to retard the rate of contaminant migration and act as mechanisms for concentration attenuation. Because of their effects, the plume of a reactive contaminant expands more slowly and the concentration is less than that of an equivalent nonreactive contaminant. Unfortunately, this retarding effect increases the cleanup time of a pump-and-treat system.

Chemical properties of the plume are necessary (1) to characterize the transport of the chemicals and (2) to evaluate the feasibility of a pump-and-treat system. The following properties influence the mobility of dissolved chemicals in ground water and should be considered for plume migration and cleanup:

1. Aqueous solubility: Determines the degree to which the chemical will dissolve in water. Solubility indicates maximum possible concentrations. High solubility indicates low sorption tendencies, e.g. methylene chloride.

2. Henry's Law constant: High values may signify **volatilization** from the aqueous phase as an important transport process, e.g. dichlorodifluoromethane (Freon 12). Used in conjunction with vapor pressure.

3. **Density**: For high concentrations, the density of the contaminated fluid may be greater than the density of pure water, e.g. trichloroethylene (TCE). This causes the downward vertical movement of contaminants.

4. Octanol-water partition coefficient: Indicates a chemical's tendency to partition between the ground water and the soil. A large octanol-water partition coefficient signifies a highly hydrophobic compound, which indicates strong sorption, e.g. DDT. This provides similar information to that provided by solubility.

5. Organic carbon partition coefficient: Another indicator of a chemical's tendency to partition

Table 2. Data pertinent to ground-water contamination characterization (from Bouwer et al., 1988).

General Category	Specific Data
Site physical framework	Estimates of hydrodynamic dispersion parameters **Effective porosity** distribution Natural (background) aquifer constituent concentration
Distributions	Fluid **density** and relationship to concentrations
System stresses	Pollution source locations Pollutant releases
Chemical/biological framework	Mineralogy Organic content Ground-water temperature Solute properties Major ion chemistry Minor ion chemistry Eh-pH environment
Observable responses	Areal and temporal distributions of water, solid, and vapor phase contaminants Stream flow quality distributions over space and time

between ground water and the soil. For certain chemicals, it is directly related to the **distribution coefficient** K_d via the fraction of organic carbon (foc).

6. Biodegradability: This provides information regarding the persistence of the chemical and which, if any, transformation products might be expected.

These parameters for many chemicals may be obtained from references such as Lyman et al. (1982) or CRC (1965). Some values are provided in Appendix A.

In addition to the data discussed above, other data may need to be collected relating to (1) in situ biological processes and (2) NAPL migration. For in situ biological processes, the additional data needed may include: (1) characterization of organisms in the subsurface, (2) analysis for chemicals required for the biological process to occur, and (3) analysis for potential transformation products (degradation compounds). In situ biological processes are important in order to estimate natural degradation and to determine if bioreclamation (an improved pump-and-treat method) is a possible remedial alternative.

NAPL data

The presence of a separate nonaqueous phase greatly complicates the contaminant characterization. Movement of a contaminant as a separate, immiscible phase is not well understood in either the saturated or unsaturated zones. A nonaqueous phase moves in response to pressure gradients and gravity. Its movement and, hence, recovery, is influenced by interfacial tension and by the processes of volatilization and dissolution.

The additional data requirements for NAPLs include: (1) fluid **specific gravity** (density), (2) fluid **viscosity**, (3) residual saturation, (4) relative permeability-saturation-capillary pressure relationships, and (5) NAPL thickness and distribution. Following a spill or release, light NAPLs tend to spread over the water table. Dense nonaqueous phase liquids (**DNAPLs**) tend to move below the water table until reaching a low-permeability barrier, such as a confining bed. Examples of DNAPLs include 1,1,1-trichloroethane, carbon tetrachloride, pentachlorophenols, dichlorobenzene, tetrachloroethene, and creosote; examples of **LNAPLs** include gasoline, heating oil, kerosene, jet fuel, and aviation gas (see Appendix A). Commonly, LNAPLs have a viscosity less than water, and DNAPLs have a viscosity greater than water (de Pastrovich et al., 1979). Following a spill, a product of low viscosity will penetrate more rapidly into the soil than a product with higher viscosity.

Residual saturation, also known as irreducible saturation, is the saturation below which fluid drainage will not occur (Figure 3). The residual saturation depends mainly on two factors: (1) the distribution of soil pore sizes, and (2) the type of immiscible fluid involved. Residual saturations are difficult to estimate accurately and are subject to considerable error.

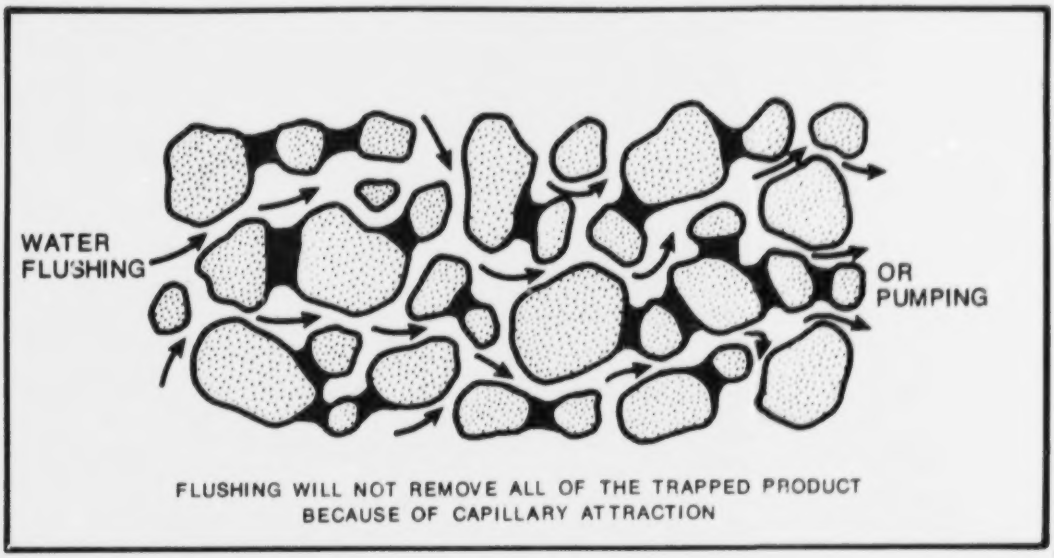

Figure 3. Trapped oil at residual saturation (from API, 1980).

The residual saturation of hydrocarbons has important consequences on soil cleanup, petroleum product recovery, and ground-water contamination. As oil moves through a soil, it leaves oil trapped at residual saturation. The amount of oil retained in the soil is normally between 15 and 40 liters per cubic meter (Fussell et al., 1981). According to API (1980), this trapped oil can last for many years as the oil slowly degrades. While residual saturation has the effect of depleting a plume of oil, thus reducing the contamination impact of pure product reaching and migrating within the saturated zone, it has the detrimental effect of providing a long-term source of miscible contaminants. For NAPLs subject to water-table fluctuations, residual saturations can occur below the water table. This has detrimental consequences for a pump-and-treat system.

When more than one fluid exists in a porous medium, the flowing fluids compete for pore space. The net result is that the mobility is reduced for each fluid. The reduction can be quantified by multiplying the **intrinsic permeability** by a dimensionless ratio, known as relative permeability, k_r. Relative permeability is the ratio of the effective permeability of a fluid at a fixed saturation to the intrinsic permeability. Relative permeability varies from zero to one and can be represented as a single-valued function of phase saturation, S. An example of relative permeabilities in a water-oil system is shown in Figure 4. Note that at residual saturation, S_r, the respective relative permeability becomes zero; that is, flow ceases to occur and product recovery stops.

Although relative permeability data are available for many petroleum reservoir engineering applications, these data are not generally available for liquids found at hazardous waste sites. Data on water and trichlorethylene (TCE) are the exception. Lin et al. (1982) made laboratory measurements of pressure-saturation relations for water-air and TCE-air systems in **homogeneous** sand columns. These data were later converted to two-phase saturation-relative permeability data by Abriola (1983).

Data collection

Conducting a background data search reduces the amount of information that will have to be collected in the field. As indicated above, chemical-specific information is available in handbooks. Various sources of general information on specific sites are available as shown in Table 3. Other sources of information are listed in U.S. EPA (1988b). Once the available data have been reviewed, it is possible to design an approach to collect the initial field data.

Subsurface conditions can be studied only by indirect techniques or by using point data. Table 4 lists common data collection methods. References on monitoring wells include Scalf et al. (1981), Driscoll (1986), and Campbell and Lehr (1973); references on geophysical techniques include Dobrin (1976), Keys and MacCary (1971), Stewart et al. (1983), and Kwader (1986). Choice of appropriate methods depends on the overall scope of the project. A

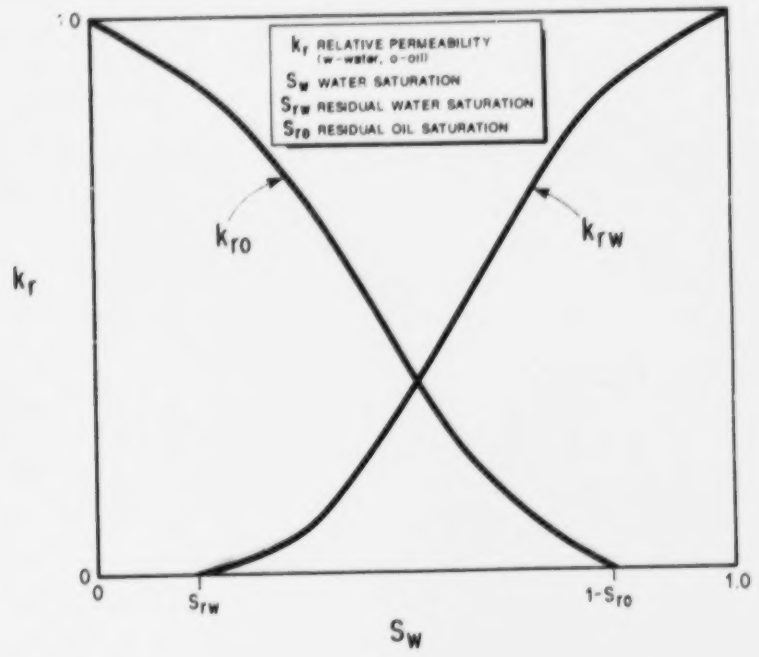

Figure 4. Water-oil relative permeability versus water saturation.

Table 3. Potential sources of information (Knox et al., 1986).

Problem Specific:	Federal or state geological surveys, university libraries, geology and engineering departments, state health departments, property owner, county records, well drillers.
Site Specific:	Weather bureaus, state water resources boards, census bureaus, soil and water conservation districts, employment commissions, corporation commissions, Department of Agriculture, Forest Service.
Other:	Medical libraries, state or federal environmental protection agencies, state attorney general's office.

Table 4. Data collection methods (references provided in text).

Category	Commonly Used Methods	Advantages/ Disadvantages
Geophysics (Indirect data method)	Electromagnetics	Good for delineation of high conductivity plumes
	Resistivity	Useful in locating fractures
	Seismic	Limited use in shallow studies
	Ground penetrating radar	Useful in very shallow soil studies
Drilling	Augering	Poor stratigraphic data
	Augering with split-spoon sampling	Good soil samples
	Air/water rotary	Rock sample information
	Mud rotary	Fills fractures - needs intensive development
	Coring	Complete details on bedrock
	Jetting/driving	No subsurface data
Ground-Water sampling	Bailer	Allows escape of volatiles (operator dependent)
	Centrifugal pump	Can produce turbid samples increasing chance of mis-represented contamination
	Peristaltic/bladder pumps	Gives more representative samples
Soil sampling	Soil boring	Restricted to shallow depths
Aquifer tests	Pump test	Samples a large aquifer section
	Slug test	Does not require liquid disposal

conceptualization of the site and contamination problem should be made and updated as data become available. Throughout the study, it is essential to document all well construction details, sampling episodes, etc., in order to arrive at an accurate evaluation of the entire site. An understanding of the hydrogeology and extent of contamination are important to a successful field study. Formulating adequate design plans ensures that wells are sited to a proper depth and stratigraphic layer so the extent of contamination is not exacerbated by cross contamination.

Methods for determining hydraulic properties of subsurface units primarily consist of aquifer tests (e.g., **pump tests** or **slug tests**). In a pump test, a well is pumped and water-level responses are measured in surrounding wells. Solutions are available for estimating aquifer parameters based on the stress (pumping) and the response (drawdown and recovery) (see, e.g., Ferris et al., 1962 or Kruseman and De Ridder, 1976). The slug test method involves inducing a rapid water-level change within a well and measuring the rate the water level in the well returns to its initial level. The initial water-level change can be induced by either introducing or withdrawing a volume of water or displacement device into or out of the well. The rate of recovery is related to the hydraulic conductivity of the surrounding aquifer material (Cooper et al., 1967; Papadopulos et al., 1973; Bouwer and Rice, 1976). The advantage of a slug test (unlike a pump test) is that little or no contaminated water will be produced. Unfortunately, slug tests measure the response in only a small volume of the permeable media, whereas aquifer tests measure the response in a much larger volume. More recently, the borehole flowmeter has been used to examine the spatial variability of hydraulic conductivity (see, e.g., EPRI, 1989).

To determine flow directions and vertical and horizontal gradients, water levels must be measured and converted to elevations relative to a datum, usually mean sea level. Water-level measurements may be taken by several different means including (1) chalk and tape, (2) electrical

water-level probe, and (3) pressure transducer. These techniques are discussed in Acker (1974) and Streltsova (1988). Horizontal gradients are determined using water-level data from wells that are open to the same hydrologic unit and/or at the same elevation but separated areally. Vertical gradients are determined using water-level data from wells in the same location but open to different elevations. The gradient is the difference in water levels divided by the distance between the measurement locations. Because water levels often yield a complex three-dimensional surface, care must be taken in computing the hydraulic gradient. The gradient determines the direction of flow. Ground-water velocity is determined by multiplying the gradient by hydraulic conductivity and dividing by effective porosity.

For fractured media and karst formations, site characterization and remediation designs are even more difficult. Techniques such as **fracture trace** analysis (Lattman and Parizek, 1964) and the use of geophysical instrumentation may be useful for locating the more permeable zones, where contaminants are most likely to be located and, thus, where extraction wells should be placed. Other characterization techniques include continuous coring, aquifer tests, and tracer tests (IAHS, 1988). For more detailed discussion on flow in the special heterogeneous conditions of fractured media, see Streltsova (1988); for karst formations, see Bögli (1980), IAHS (1988), and Quinlan and Ewers (1985).

To ensure proper quality assurance (QA) and quality control (QC) of ground-water samples, strict protocols must be followed in the field. The pH, temperature, and specific conductance of a sample should be measured. Ideally, before a sample is gathered, water should be extracted from the well until these parameters have stabilized. This will help ensure that the sample is from the formation. Proper sample storage and shipment to a qualified laboratory is also important. A sampling plan should address issues such as sampling frequency, locations, and statistical relevance of samples (U.S. EPA, 1987b). For more details on sampling guidance, see Cartwright and Shafer (1987), Barcelona et al. (1983), and Barcelona et al. (1985). For methods to determine partition coefficients from cores, see Sundstrom and Klei (1979); for NAPL characterization, see API (1989).

Data Interpretation

Uncertainties associated with hazardous waste problems include: (1) contaminant source characterization and (2) extrapolating/ interpolating subsurface point data. Interpretation of point data begins by plotting the data and viewing it from different perspectives. For example, water-level data for specific times should be contoured to form potentiometric maps that are interpreted with respect to geologic sections and information on hydraulic conductivity. For a steady flow system, a region of higher hydraulic gradient on the potentiometric maps should correspond to a region of lower hydraulic conductivity on the geologic section. Further graphical interpretation should be made using contaminant plume maps. Plume development in the down-hydraulic-gradient direction should be noted. Different data types should be used to support other data so a conceptualization can be developed that is consistent with all data.

For example, consider a site involving heavy metal contamination where the aquifer consists of a permeable alluvium overlying a low permeability saprolite that is above permeable weathered bedrock. Concentration data plotted on a map of the area shows an irregular shape difficult to interpret, but that appears to indicate a limited and disconnected contamination problem, suggesting multiple plumes. However, looking at well construction data reveals a different picture. Wells constructed in the alluvium and weathered bedrock show contamination while those constructed in the low-permeability saprolite do not. Absence of contamination in the saprolite wells does not indicate a clean section; it only indicates that the contamination in that section has not penetrated the low-permeability saprolite. Reexamination of these data reveals that the contamination probably consists of a plume in each permeable layer that is more extensive than was thought originally when examining only a single concentration map and zero values for the saprolite wells. The original interpretation was made without considering stratigraphic effects on the three-dimensional flow system. This emphasizes the importance of examining all data, including well construction information, when characterizing contamination and designing a remediation.

The next step in data interpretation is making scoping calculations such as using the hydraulic gradient, hydraulic conductivity, and porosity in Darcy's equation to estimate convective transport. Next, one may compare these velocity calculations with estimates of mean plume movement. If the two are not comparable, this could indicate uncertainty in the source release or location or that processes such as sorption or transformation are important. Inconsistences among data need to be explained. Resolving data inconsistencies assures an understanding of the site and reduces uncertainty.

There are numerous tools that can be used to interpret data, including:

Geochemical analysis - Methods such as ion-association models can be used to interpret chemical changes in the aquifer. Representative models include MINEQL (Morel and Morgan, 1972), WATEQ2 (Ball et al., 1979), EQ3 (Wolery, 1979), and MINTEQA1 (U.S. EPA, 1987b).

Geostatistical analysis - Methods such as kriging can be used to quantify the spatial variability inherent in the hydraulic conductivity field of an aquifer (see, e.g., Journal, 1978 or Englund and Sparks, 1988). For uncertainty, kriging provides confidence intervals for the parameter of interest (Cooper and Istok, 1988a and b). Statistical methods may be used to determine the

relationship among various parameters and help define the statistical likelihood of a particular occurrence (Davis, 1973 and Gilbert, 1987).

Mathematical modeling - Models such as the three-dimensional, finite-difference flow code MODFLOW (McDonald and Harbaugh, 1984) and the semianalytical flow code RESSQ (Javandel et al., 1984) can be used to simulate flow patterns and changes resulting from the operation of a pump-and-treat system. Other models are available to analyze contaminant transport (see, e.g., van der Heijde et al., 1985 or U.S. EPA, 1988c). To address uncertainty, one may use discrete sensitivity analysis where a parameter is varied and its impact on the concentration is assessed.

Parameter uncertainties are a consequence of the estimation procedure and spatial and temporal variability in model parameters. Various techniques are available to handle the effects of parameter uncertainty in ground-water flow. These techniques can be divided into two broad categories: full distribution analyses, and first and second moment analyses (Dettinger and Wilson, 1981). Full distribution analyses require a complete specification of the probability functions (pdfs) of the random variables or parameters. These pdfs are either known or assumed. The most common full distribution techniques are the method of derived distributions (Benjamin and Cornell, 1970), the Monte Carlo method (Kalos and Whitlock, 1986) and the Latin hypercube method (Iman and Shortencarier, 1984).

Conceptual Design

Because of complex site conditions, it may be necessary to combine remedial actions into a treatment train. Choosing a remedial technology is a function of the contaminant and its reactivity and mobility, characteristics of the site (e.g., hydraulic conductivity), and the location of the contaminant (e.g., above or below the water table). The ease with which the contaminant moves through the subsurface determines how extensive and how difficult it will be to remediate the contamination problem. For example, a formation must have sufficient hydraulic conductivity to allow pumpage. If a shallow aquifer is very tight (low hydraulic conductivity), pumping at a reasonable rate may cause the well to go dry, creating a capture zone that is too limited. For such conditions, an intercept drain may be more appropriate. The reactivity of a contaminant, either chemically or biologically and its ultimate fate determine whether an in situ treatment process can be used or whether containment or physical removal is more effective. If a volatile compound, such as gasoline, is above the water table, pumping (or skimming) may recover the petroleum product, but will leave a residual product that a vacuum extraction (soil venting) system might recover. Thus, pump-and-treat technology may be combined with other technologies to complete remediation in the saturated and vadose zones.

Pump-and-treat technology is appropriate for many hydrogeological conditions, waste types, and chemical properties. It may be necessary, however, to combine a pump-and-treat system with other technologies (e.g., bioreclamation, soil venting) or to make system adjustments (e.g., pulsed pumping). It is important to be aware of the time frames that may be required to achieve a particular remedial objective (cleanup goal) before deciding on a pump-and-treat remediation.

There may be situations where pump-and-treat technology will not effectively remove contaminants. An example is dense nonaqueous phase liquids (DNAPLs) at residual saturation. Unfortunately, this is a very difficult problem for which other remedial options may not be effective either. If the residual DNAPLs are shallow, then excavation may be a reasonable option. If they are too deep to excavate, then pump-and-treat technology is a possible remedial action to hydraulically contain any dissolved contamination. Containment may be required until a technology is developed (e.g., enhanced oil recovery methods) that can treat or remove the DNAPLs. An area where containment is being implemented is the S-Area site in Niagara Falls, New York (Cohen et al., 1987). Here, a combination of physical and hydraulic barriers was proposed to contain DNAPLs (Figure 5). When containment is selected, seasonal or transient ground-water flow conditions must be considered to insure year-round containment.

One way to evaluate the effectiveness of a remediation is through a study a case histories. Lindorff and Cartwright (1977) discuss 116 case histories of ground-water contamination and remediation. U.S. EPA (1984a and b) presents 23 case histories of ground-water remediation. More recently (U.S. EPA, 1989), ground-water extraction has been evaluated via case histories. The results of this latter study are summarized in Appendix B.

When to select pump-and-treat systems

Figures 6a and 6b present decision-flow diagrams for ground-water contamination and soil contamination, respectively. For ground-water contamination, the first decision concerns whether a remedial action (G3) is necessary. If a risk assessment shows the need for a remedial action, then the options shown in Figure 6a are containment (G4), in situ treatment (G5) or pump and treat (G6). If G5 is selected, then other decisions are necessary but not discussed here. If G4 is selected, then the containment can be either physical (G7) or hydraulic (G8). Physical containment has generally not worked well (Mercer et al., 1987) and is not discussed further; hydraulic containment is achieved by pump-and-treat technologies (G11). As indicated previously, if the source of the ground-water contamination is not removed, then containment may be necessary as opposed to G5 or G6.

If pump and treat (G6) is selected, the next decision is whether to use wells (G9) or drains (G10). If the hydraulic conductivity is sufficiently high to allow flow to wells, then select wells. For low-permeability material, drains may be

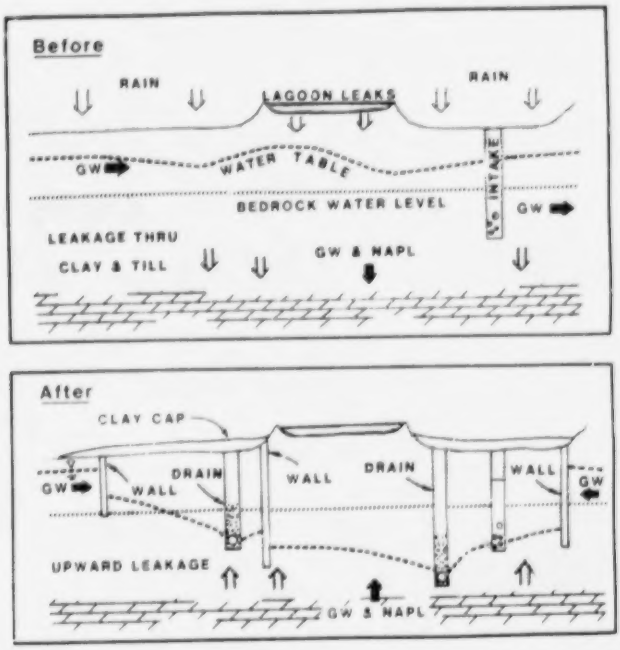

Figure 5. S-Area site, Niagara Falls, New York, showing proposed containment system.

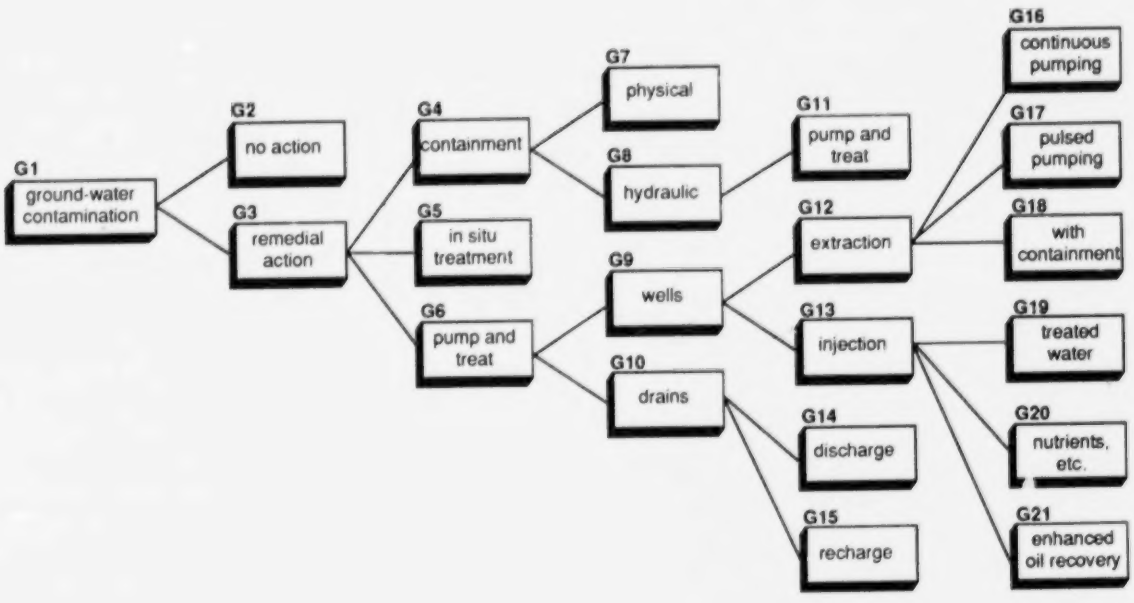

Figure 6a. Decision-flow diagram for ground-water contamination.

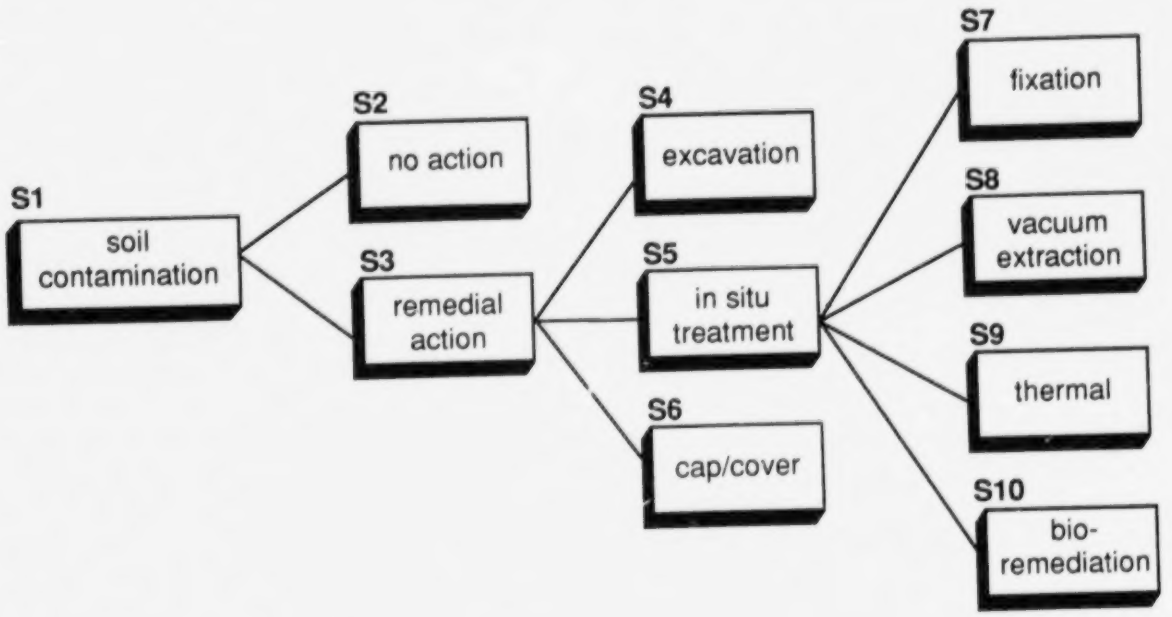

Figure 6b. Decision-flow diagram for soil contamination.

required. After wells have been selected, a decision must be made concerning whether they are extraction wells (G12), injection wells (G13), or a combination. Injection wells will reduce the cleanup time by flushing contaminants toward the extraction wells. For the extraction wells, decisions need to be made concerning continuous pumping (G16), pulsed pumping (G17), and/or pumping combined with containment. Continuous pumping maintains an inward hydraulic gradient; pulsed pumping allows maximum concentrations to be extracted efficiently; containment can be used to limit the inflow of clean water that needs to be treated. The injected water can be treated water (G19); for biodegradable contaminants, it can contain nutrients and/or electron acceptors (G20) to enhance in situ **biodegradation**; or, for NAPLs, it can consist of enhanced oil recovery (**EOR**) materials (G21). For further information on EOR techniques, see Shah (1981). For problems involving ground-water contamination, some form of pump-and-treat technology will almost always be used.

A similar decision process can be followed for soil contamination (Figure 6b). The first decision is no action/remedial action. For a remedial action, the choices are excavation (S4), in situ treatment (S5), and/or cap/cover (S6). For in situ treatment, the options are fixation (S7), vacuum extraction (S8), thermal (S9), or bioremediation (S10). Vacuum extraction is possible if the contaminants are volatile. Other options may be available; however, soil cleanup is not the emphasis here and, therefore, is not given greater discussion. Most contamination problems will impact both soil and ground water. For such problems, a combination, e.g., G6 and S8, of options may be required to achieve cleanup.

Example of contaminant plume delineation and pump-and-treat implementation

This example is based on a study at a facility that uses many solvents that are potential pollutants. No previous site-specific studies had been conducted; hence, the existence and extent of contamination were unknown. The investigative work was performed in three phases.

Phase 1

During Phase 1, an evaluation was made of the site hydrogeology and ground-water quality. Regional studies were obtained from the state geological survey, the local water authority, and Soil Conservation Service; prior construction information was obtained from the company. A list of all on-site potential contaminant sources was prepared Potential preferred flow paths were identified by performing a fracture trace analysis (see, e.g., Lattman and Parizek, 1964) using aerial photographs of the site. Water levels from existing wells on-site and just off-site were used to develop preliminary ground-water flow directions.

The site geology consists of overburden underlain by interbedded sandstones, siltstones, and shales. Ground-water flow was concentrated in linear fracture zones. The

hydrogeologic system consisted of two aquifers: a confined zone about 400 feet deep and an upper semiconfined zone from the surface to a depth of 200 feet. Flow directions in the deep zone could not be determined. Ground-water levels revealed that flow was toward the northwest (in a direction toward a local water supply well) in the shallow zone. Using this information and the geological/hydrogeologic framework, monitoring well locations were sited in flow paths that might contain contamination. Initially, three monitoring wells were installed downgradient of suspected source areas and an ex[illegible] well was used for upgradient information. Off-site a[illegible]site wells in the deep aquifer showed no signs of co[illegible]ation; however, moderate concentrations of the so[illegible]its trichloroethene (TCE) and tetrachloroethene (PCE) were found in a limited portion of the shallow zone.

Phase 2

After identifying an area of contamination, a **soil gas survey** (see, e.g., Marrin and Thompson, 1984) was performed to determine if the source of contamination still existed. The soil gas survey revealed concentrated levels of PCE and TCE in a limited area of the overburden. Soil contamination was verified through a soil sampling program. The contaminated soil was removed and replaced with clean fill. Additional monitoring wells were installed to define the plume boundaries and to provide water quality data. These data were used to determine the areal and vertical extent of the contaminant plume, which appeared to be limited in extent and confined to the top portion of the upper aquifer. To account for seasonal variations, the wells were monitored for approximately six more months. At the end of that time, the third phase was initiated.

Phase 3

Water quality and water-level monitoring showed that removing the contaminated soils probably eliminated the source of the contamination. That is, the plume rate of movement was very slow with decreasing concentration with time. The concern was the movement of dissolved TCE and PCE in the ground water. Therefore, for this phase of field work, a series of slug and pump tests were conducted.

The slug test data provided estimates of the hydraulic conductivity of the aquifer immediately adjacent to the boreholes. Pump tests were conducted using downgradient wells in high-hydraulic conductivity zones (based on slug tests) to determine their areas of influence. The tests were analyzed to determine hydraulic conductivity. Hydraulic conductivities and porosity estimates, along with the water-level data, were used to determine convective plume movement. Using these analyses and data on the geologic/hydrogeologic framework, a pump-and-treat system was selected where:

1. Locations of two extraction wells maximizing capture of the plume horizontally and vertically were chosen.
2. The most efficient pumping rate of 20 gpm was determined.
3. Pumping would not impact any off-site facility or well.
4. The location for injection of the treated water was chosen to complement the pumping system.

A three-year time frame was estimated to reduce the aquifer contamination to acceptable levels based on advective calculations. During this period, water quality and flow analysis continued on a quarterly basis to ensure cleanup. The pumping system derived the majority of its flow from the fracture system. Once pumping was terminated, residual contamination remained in the overlying sediments that could migrate into the cleaned region. Therefore, monitoring was continued to verify cleanup.

A phased approach provided time to refine data collection techniques and concepts of the mechanisms/processes controlling contaminant migration. The slow-moving plume allowed time for adequate study. At the end of each phase, there were sufficient data to make decisions concerning the next phase. Pump-and-treat remediation was appropriate for this case and was efficient only after a substantial portion of the source (contaminated soil) was removed.

Calculating the estimated cleanup time

The following example illustrates a simple method used to estimate the time required to achieve cleanup (Hall, 1988). Assume that an area of ground-water contamination is ten acres; the aquifer is permeable and is 55 ft thick; water in storage amounts to 30% of the aquifer's volume; and the water is contaminated with a nonreactive solute. Under these conditions, it would be possible, with a properly designed pump-and-treat system, to exchange one pore volume of water in this ten-acre plume in about a year with a pumping rate of 100 gal/min:

volume of contaminant =

10 acres x 43,560 ft²/acre x 55 ft x 7.48 gal/ft³ x 0.3 = 5.4 x 10^7 gallons

Pumping rate to remove this volume in one year = 5.4 x 10^7 gallons/365 days/1440 min/day = 102 gallons per minute.

In reality, however, it will be necessary to pump longer than one year to reach an acceptable concentration due to the **"tailing"** effect often observed with this remedial action. Tailing is the asymptotic decrease of contaminant concentration in water that is removed in the cleanup process (Figure 7). Compared to ideal removal, tailing requires longer pumping times and greater volumes pumped to reach a specific cleanup concentration goal. Tailing may be caused by several phenomena. For example, a highly-soluble and mobile contaminant can migrate into less-permeable zones of the geologic material. Here it will slowly exchange with the bulk water flowing in the more-permeable zones and will be removed less readily. As a result, it will be necessary to pump ground water that was

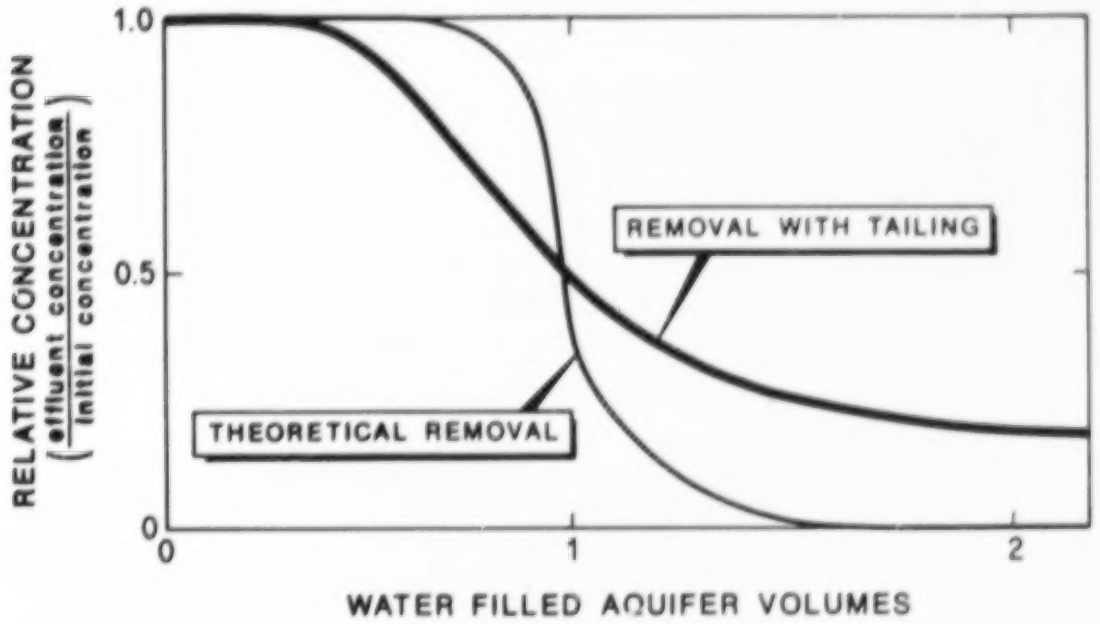

Figure 7. Effects of tailing on pumping time (from Keeley et al., 1989).

originally outside the chemical plume to complete aquifer cleanup.

For a reactive sorbing compound, the time required to remove the contaminant by pumping is increased. Consider the previous and following examples (Hall, 1988). The contaminated area is 10 acres (660 ft by 660 ft). If the aquifer is 55 feet thick and ground-water flow is from one side of the contaminated zone to the other with a volume discharge of 100 gpm and a porosity of 0.3, then the **interstitial velocity** of the water would be approximately:

$$100\ \text{gal/min} \times 1440\ \text{min/day} \times 1\ \text{ft}^3/7.48\ \text{gal} \times 365\ \text{days/year} \div (660\ \text{ft} \times 55\ \text{ft} \times 0.3) = 645\ \text{ft/yr}.$$

Hence, it will take water approximately one year to travel through the contaminated area.

If the **bulk density** of the soil is 100 lb/ft^3, the density of water is 62.4 lb/ft^3, and the **linear soil partition coefficient** is 0.75 (ratio of mass concentration on solid phase to mass concentration in the aqueous phase), then the time for the contaminant to traverse the same distance is calculated from:

$$\text{contaminant velocity} = \text{water velocity/retardation factor}$$

$$\text{retardation factor} = 1 + [\text{soil partition coef.} \times \text{soil bulk density}/(\text{water density} \times \text{porosity})]$$

Thus, the contaminant would travel at 129 ft/year and would take five years to traverse the length of the contaminated area. The cleanup time is thus increased because of the slower contaminant movement toward the extraction wells. In addition, the tailing effect is amplified due to desorption. That is, as the ground-water plume is reduced in concentration as a result of pumping, the contaminant will desorb from the soil and maintain the ratio of the partition coefficient.

Limitations of pump-and-treat systems

Any time extensive ground-water contamination exists, pump-and-treat systems should be considered; they should be accepted, rejected, or combined with other remedial technologies based on a site-specific analysis. Pump-and-treat systems may be the only option when deep ground-water contamination exists. Properly designed and accurately located extraction wells are effective for containing and/or remediating ground-water contamination, but have limitations. For many contaminants, reducing ground-water concentrations to Safe Drinking Water Act or Land Disposal Restriction standards is a difficult task. Favorable and unfavorable conditions for the application of pump-and-treat technology are listed in Table 5.

Table 5. Favorable and unfavorable conditions for pump-and-treat technologies.

Favorable Conditions	Unfavorable Conditions
SOURCE TERM	
Source removed	NAPLs at residual saturation
CHEMICAL PROPERTIES	
Mobile chemicals	Chemicals sorbed or precipitated
HYDROGEOLOGY	
High hydraulic conductivity (e.g., $K > 10^{-5}$ cm/s)	Very low hydraulic conductivity (e.g., $K < 10^{-7}$ cm/s)
Homogeneous	Highly heterogeneous

Limitations due to NAPLs

For pump-and-treat technology to remediate an aquifer in a timely fashion, the contaminant source must be eliminated. This is because unremoved contaminants will continue to be added to the ground-water system, prolonging cleanup. Excavation is one of several options available for source removal. NAPLs at residual saturation are one of the more difficult sources of ground-water contamination with which to deal. Of particular difficulty are substances such as halogenated aliphatic hydrocarbons, halogenated benzenes, phthalate esters and polychlorinated biphenyls which, in their pure form, are DNAPLS. When NAPLs are trapped in pores by interfacial tension, diffusive liquid-liquid partitioning controls dissolution. Flow rates during remediation may be too rapid to allow aqueous saturation levels of partitioned contaminants to be reached locally (see Figure 8). If insufficient contact time is allowed, the affected water may be advected away from the residual NAPLs before approaching chemical equilibrium and is replaced by water from upgradient. Because ground-water extraction is not generally efficient at cleaning up this type of source, some other remedial action may be required.

DNAPL example

Consider a 1 m^3 volume of sandy soil with a residual DNAPL content of 30 L/m^3. For this example, ground-water flows through the soil at a rate of 0.03 m/d, typical of ground-water conditions in a sandy soil (based on a hydraulic conductivity of 10^{-5} cm/s, a hydraulic gradient of 1% and a porosity of 30%). Furthermore, it is assumed that DNAPLs dissolve into the ground water to 10% of their solubility. For trichloroethene (density of 1.47 g/cm^3 and solubility of 1,100 mg/l), approximately 122 years would be required to dissolve the DNAPLs:

mass to be dissolved =
(30 L/m^3) (1 m^3) (1.47 g/cm^3) (100 cm^3/m^3) ($1x10^{-6}$ m^3/L) = 44,100 g

concentration of solute = (10%) (1,100 mg/L) = 110 mg/L

mass flux through 1 m^2 area =
(0.03 m/d) (1 m^2) (110 mg/L) (10^{-3} g/mg) (10^3 L/m^3) (0.3) = 0.99 g/d

time required to dissolve =
(44,100 g) ÷ (0.99 g/d) = 44,545 d ÷ (365 d/y) = 122 y

These calculations indicate that the time DNAPL chemicals can potentially remain in the subsurface is measured in years to decades or more under natural ground-water flow conditions.

Limitations due to sorption

As discussed previously and shown in Table 5, mobile chemicals may be treated using pump-and-treat technology. For sorbing compounds, however, the number of pore volumes that will need to be removed depends on the sorptive tendencies of the contaminant and the geologic materials through which it flows, as well as the ground-water flow velocities during remediation. If the velocities are too rapid to allow contaminant levels to build up to equilibrium concentrations locally (see Figure 9), then the affected water may be advected away before approaching equilibrium. Efficiency in contaminant removal may be low and will tend to decrease with each pore volume removed.

For linear sorption, a distribution coefficient can be defined for many chemicals. This may be used to define a retardation factor as:

retardation factor = 1 + [distribution coefficient x bulk density ÷ porosity]

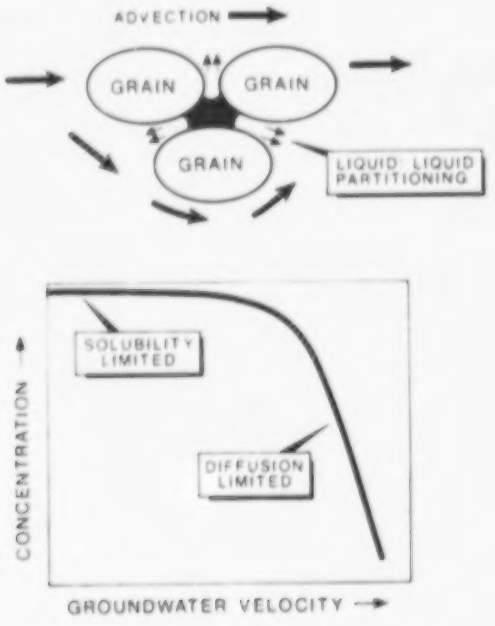

Figure 8. Liquid partitioning limitations of pump-and-treat effectiveness (from Keely, 1989).

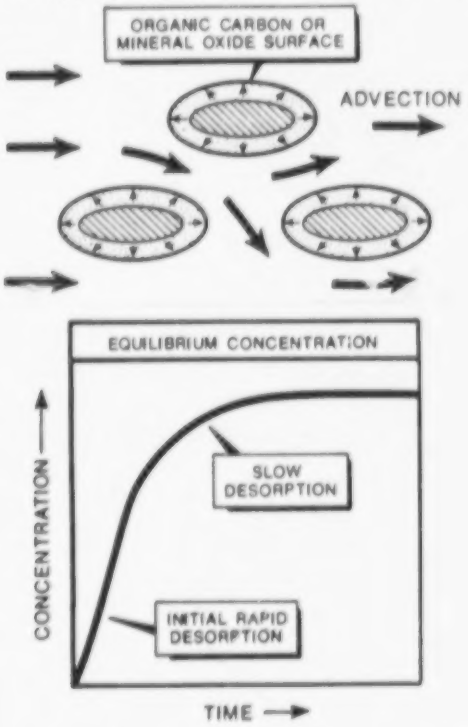

Figure 9. Sorption limitations to pump-and-treat effectiveness (from Keely, 1989).

The retardation factor indicates the speed of a contaminant relative to the water velocity. For example, dissolved tetrachloroethene (PCE) was found to have a distribution coefficient of 0.2 ml/g in a porous medium with a bulk density of 1.65 g/cm^3 and a porosity of 0.25. Using the above formula, the velocity of the PCE is approximately 40% of the water flow through the same porous media. Thus, sorption retards the movement of PCE. Unfortunately, for pump-and-treat remediation, sorption increases the time of cleanup. As indicated in a later example, an almost linear relationship exists between retardation and time of remediation for a specific cleanup level. For example, for PCE, it would take 40% longer to reach a cleanup goal compared to the cleanup time for a nonsorbed compound. This assumes no degradation.

Limitations due to low hydraulic conductivity

The hydrogeological conditions favorable to pump-and-treat technology are high hydraulic conductivity (greater than about 10^{-5} cm/s) and homogeneity. Unfavorable conditions include very low hydraulic conductivity and significant heterogeneity. If the hydraulic conductivity is too low (less than about 10^{-7} cm/s) to allow a sustained yield to a well, ground-water extraction via pumping wells is not feasible. Determining pump-and-treat feasibility is site specific; a hydraulic conductivity range that works at one site may not work at another site. For example, if the plume is small and the natural hydraulic gradient is low, a pump-and-treat system pumping at a very low rate in a low hydraulic conductivity unit may be feasible. However, this same hydraulic conductivity may result in containment failure at another site.

For heterogeneous conditions (Figure 10), advected water will sweep through zones of higher hydraulic conductivity, removing contamination from those zones. Although heterogeneous conditions only are illustrated in the vertical in Figure 10, they are generally a three-dimensional phenomenon. Movement of contaminants out of the low hydraulic conductivity zones is a slower process than advective transport in the higher hydraulic conductivity zones. The contaminants either are slowly exchanged by diffusion with the flowing water present in larger pores or move at relatively slower velocities in the smaller pores. A rule of thumb is that the longer the site has been contaminated and the more lenticular (layered) the geologic material, the longer will be the tailing effect. The water and

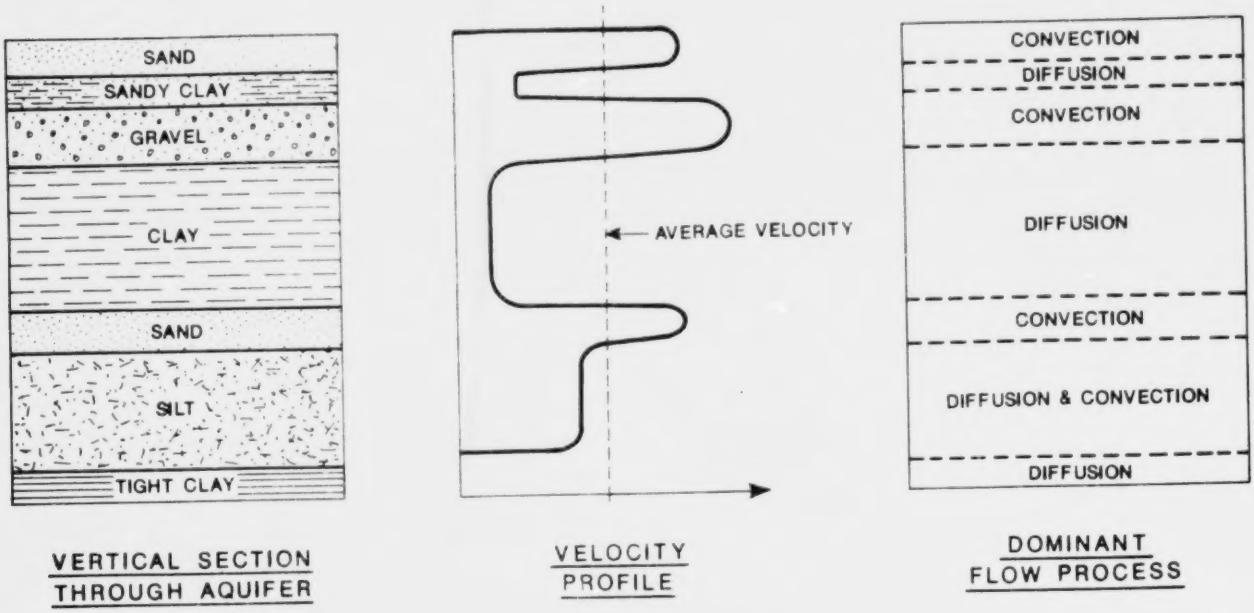

Figure 10. Effect of geologic stratification on tailing (from Keeley et al., 1989).

contaminants residing in the more permeable zones are those first mobilized during pumping. Thus, pump-and-treat technologies work in heterogeneous media, but cleanup times will be longer and more difficult to estimate than for similar systems in more homogeneous media.

Design considerations

In designing a pump-and-treat system, there are many practical aspects that must be considered including: (1) wells, (2) pumps, and (3) piping. Methods of drilling, well design, and construction are discussed in Driscoll (1986), whereas well construction effects such as partial penetration, partial screening, and incomplete development are discussed in Keely (1984).

When dealing with NAPLs, special care is required to avoid capillary barrier problems in the well construction materials. Iron or manganese may oxidize and cause clogging. Wells should be designed for ease of flushing screens and treating clogging problems. A long-term aquifer test (greater than several days) provides useful information and can serve as a prototype before the main pump-and-treat system is designed. Pumps are also discussed in Driscoll (1986); consideration should include failure rates, reaction to contaminants, and ease of maintenance. Back-up pumps should be available in the event of pump failure. For pipelines, clogging and freezing problems should be considered, as well as techniques for monitoring flow rates (e.g., flow meters). Be conservative when sizing pipes and the treatment system in case increased pumpage is required. Include provisions for insulation of piping to prevent freezing, particularly for systems with intermittent operation. Although these aspects of pump-and-treat design are important, the emphasis here is on analysis techniques for performing site-specific evaluation.

Determining well spacings, pumping rates, and time required for cleanups

At many sites, it is advantageous to have multiple extraction wells pumping at small rates versus one well pumping at a large rate. Analytical or numerical modeling techniques are used to evaluate alternative designs and help determine optimal well spacings, pumping rates, and cleanup times (see, e.g., U.S. EPA, 1985). For example, a generic modeling study examining the effectiveness of various restoration schemes is presented in Satkin and Bedient (1988). There also are approaches combining ground-water models with linear and nonlinear optimization (see e.g., Gorelick et al., 1984). Fluid pathlines and travel times in ground-water systems also can be estimated from particle tracking codes (see e.g., Shafer, 1987). In addition, there are numerous analytical solutions that may be used to estimate pumping rates and well spacings once aquifer properties are known. These solutions are included in Ferris et al. (1962), Bentall (1963), Walton (1970), and Jacob (1950). In the following examples, both numerical and analytical models were used to estimate well spacings, pumping rates, and cleanup times.

Using a numerical model

A proposed pump-and-treat system for a hazardous waste site was evaluated using a numerical model and is described by Ward et al. (1987). The goal of the pump-and-treat system was to contain and clean up contamination. The results of the transport simulations are summarized in Figure 11. This figure shows the distribution inventory of the mass of volatile organic compounds (VOC) at the site over time. At any given time, the initial VOC mass can be distributed in three categories: (1) mass remaining in ground water, (2) mass removed by the extraction system, and (3) mass leaving the domain unremediated. The mass in ground water diminishes with time. However, some mass leaves the system uncaptured by the proposed corrective action. Thus, this pump-and-treat system will fail to contain the contamination.

To assess the effect of increasing discharge and injection rates on plume capture, simulations were performed in which the total extraction and injection rates were doubled. The increased pumping rates decreased the VOC mass left in ground water but still failed to contain a portion of the plume (indicated by the dashed line in Figure 11). Thus, final pumping rates will need to be even greater. These results show the importance of plume capture analysis and emphasize the need for performance monitoring and the use of a model in monitoring program design.

The analysis of the above pump-and-treat system indicated declining contaminant concentration at the seven proposed extraction wells with time (Figure 12). Most wells exhibit a decreasing trend after a few weeks of operation. For each tenfold increase in the time of system operation, the concentration of VOCs decreases by a factor of ten. Some wells exhibit a temporary increase in concentration as zones of contamination are flushed toward the extraction wells. The effect of sorption also was examined with the model. A nearly linear relationship exists between retardation and time of remediation for a specific level of contaminant.

Using an analytical model

The preceding example illustrates how a numerical model may be used to evaluate pumping rates and cleanup times. Other tools are available that allow for similar evaluations. Scoping calculations to estimate the pumpage required to capture a plume in a **confined aquifer** may be performed using the semianalytical model RESSQ (Javandel et al., 1984, and Javandel and Tsang, 1986). RESSQ is applicable to two-dimensional contaminant transport subject to advection and sorption (no dispersion, diffusion, or degradation can be considered) in a homogeneous, isotropic, confined aquifer of uniform thickness when regional flow, sources, and sinks create a steady-state flow field. Recharge wells act as sources and pumping wells act as sinks. RESSQ calculates ground-water flow paths in the

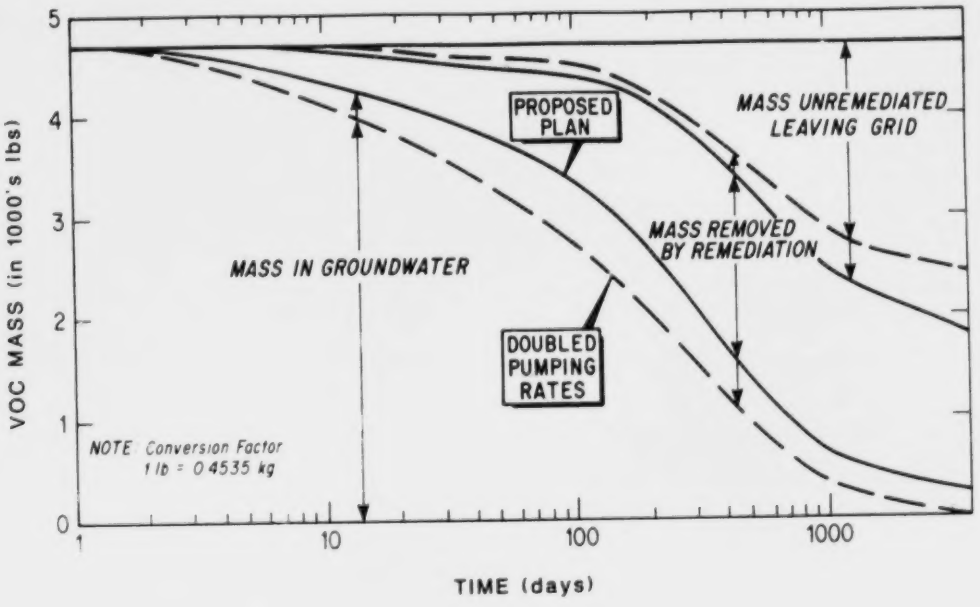

Figure 11. Calculated VOC inventory versus time (from Ward et al., 1987).

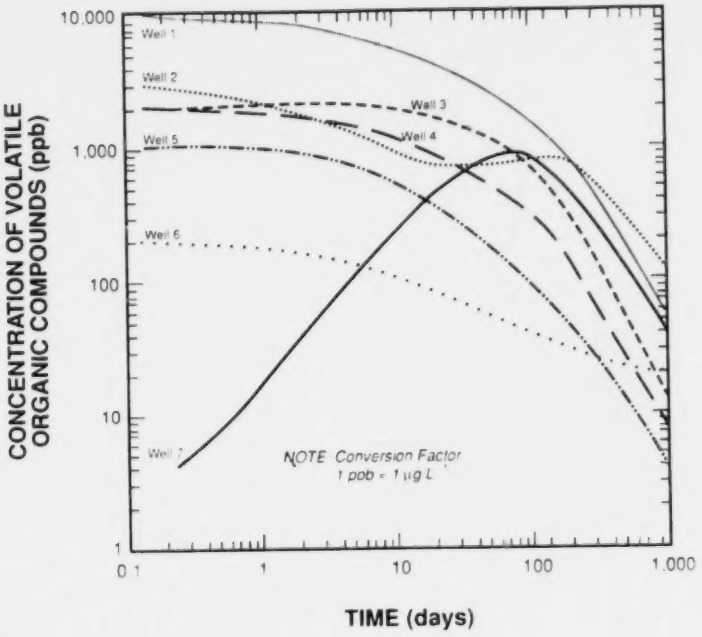

Figure 12. Calculated extraction well concentrations versus time (from Ward et al., 1987).

aquifer, the location of contaminant fronts around sources at various times, and the variation in contaminant concentration with time at sinks. An example of how RESSQ can be used to determine optimum pumping rates and well spacings is presented below.

The site is located in glacial deposits and consists of a leaking landfill with an associated plume (Figure 13). The goal is to design a capture well network for the plume. The site is more complex than the conditions simulated with RESSQ. There is a convergent flow field caused, in part, by a sand lens (not shown). This causes the plume to narrow with distance from the landfill. For these scoping calculations, the flow system considered is at the front of the plume, where the wells are placed. For this location, a ground-water velocity of 0.205 ft/d (75 ft/yr) was estimated using Darcy's equation. The aquifer is 30 feet thick and the plume width is approximately 600 feet. The regional flow rate is: 600 ft x 30 ft x 0.205 ft/day = 3690 ft^3/day or 19.2 gpm. The total pumping rate of the wells will need to be approximately 20 gpm to capture the plume. Using this pumping rate, flow lines computed by RESSQ (see Figure 13) will capture the plume.

Next, the maximum pumping rate that is sustainable without the wells going dry must be determined. The computation of drawdown at a single well in a multiple-well installation is not precise when a single **water-table aquifer** of infinite extent is assumed. For 10 wells pumping at 2 gpm each, the maximum drawdown is calculated using the Theis solution and **superposition** (see, e.g., Walton, 1970) as 32 feet. This is an overestimate, as the leakage from the layers below and other sources (e.g., delayed yield) in the vicinity is not considered. Therefore, 10 wells at 2 gpm is deemed acceptable from the considerations of drawdown.

An optimum well spacing of 25 ft was determined based on guidelines provided by Javandel and Tsang (1986). Streamtubes representing uniform regional flow were generated in the RESSQ simulations (Figure 13). The streamtubes trace the movement of the contaminants in the plume by advective transport. To ensure that contaminants do not escape between a pair of wells, the two streamtubes at the middle of the plume were divided into 5-foot wide spacings. The resulting calculations using RESSQ confirmed that the proposed pumping system would effectively capture the plume.

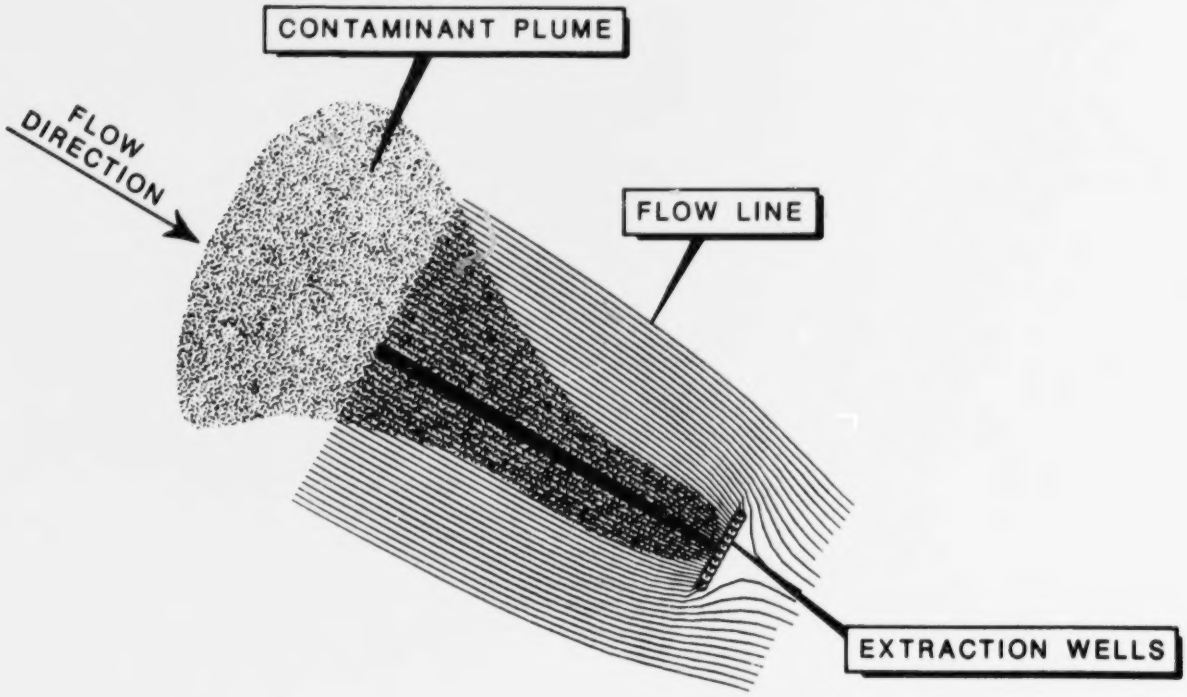

Figure 13. Simulation to capture front of the plume: 10 wells, 25 feet apart, pumping at 2 gpm each.

Example of a gasoline spill

Brown et al. (1988) present an evaluation of the effectiveness of a pump-and-treat system for remediating a gasoline spill. Petroleum hydrocarbons can exist in the subsurface as: mobile free product, immobile residual, vapor, and as solute in ground water (dissolved phase). The distribution of hydrocarbons under these different conditions is a function of their physical and chemical properties, and the hydrogeological and geochemical characteristics of the formation. The distribution can be defined by: (1) the areal extent of contamination and the volume of the subsurface impacted by a phase or (2) the amount of the contaminant within a phase, measured as either total weight or concentration.

Table 6 represents the phase distribution of the gasoline spill in a sand-and-gravel aquifer. In this case, both the solubility of the contaminant and the sorptive properties of the formation are low. Consequently, most of the contaminant (91% of the amount spilled) is light nonaqueous phase liquids (LNAPLs). However, because of the low concentration and high mobility of the dissolved component of gasoline in ground water, the areal extent of ground-water contamination is greater than the LNAPLs. The dissolved phase, however, contains only a small fraction of the total mass.

Several observations can be made from Table 6. Pump-and-treat technology is effective at recovering free product - 126,800 lb or 91% of the mass was recovered. Because this is a sand-and-gravel aquifer, pumping contaminated ground water will be effective also. However, the maximum contaminant level (**MCL**) for benzene, a component of gasoline, is 5 ug/l. The time frame to reach this remedial objective will be very long because the solubility of gasoline at residual saturation is low. Therefore, soil contamination (residual gasoline) represents a significant source of ground-water contamination. Brown et al. (1988) examined the effectiveness of pump-and-treat technology for cleanup of residual gasoline using laboratory studies. Their results show that ground-water extraction is not effective in treating residual saturation.

Pumping the LNAPLs removes most of the mass effectively. Pumping the contaminated ground water is effective but is efficient only if the contamination source (residual gasoline) is remediated. Pump-and-treat technology is not effective at removing the residual. Therefore, once the mobile LNAPLs are removed, another technology (such as soil venting or bioreclamation) must be used for the contaminant source in the soil so that ground-water extraction and cleanup can be accomplished in a reasonable time.

Table 6. Phase distribution of gasoline in sand and gravel (Brown et al., 1988).

	Extent of Contamination		*Mass Distribution*		
Phase	Volume, cu yd	% of Total	lb	Conc. ppm	% of Total
Free phase[1]	780	5.3	126,800[1]	--	90.9
Residual	2,670	18.3	11,500	2,000	8.2
Dissolved	11,120	76.3	390	15	0.3

[1]Actual value recovered from site through pumping

Operation and Monitoring

Whatever remediation system is selected for a particular site, the following items need to be described clearly:

- remedial action objectives,
- monitoring program, and
- contingencies (modification to the existing remediation).

Remedial action objectives are the goals of the overall remediation. To ensure that these are met, appropriate monitoring must be conducted. If the monitoring indicates that the goals are not being met, then contingencies must be specified concerning changes to the remediation system that will ensure that the goals are reached, or will specify alternate goals where original goals cannot be practically achieved.

Remedial action objectives

According to Keely (1989), numerous monitoring criteria and monitoring point locations are used as performance standards. Monitoring criteria can be divided into three categories: chemical, hydrodynamic, and administrative control. Chemical monitoring criteria are risk based (U.S. EPA, 1986b) and include Maximum Contaminant Levels (MCLs), Alternate Concentration Limits (ACLs), detection limits, and natural water quality. Hydrodynamic compliance criteria may include demonstrated prevention or minimization of infiltration through the vadose zone, maintenance of an inward hydraulic gradient at the boundary of the contaminant plume, or providing minimum flow to a surface water body. Administrative control monitoring criteria range from reporting requirements, such as frequency and character of operational and post-operational monitoring, to land-use restrictions, such as drilling bans and other access-limiting restrictions.

Monitoring

Once the remedial action objectives are established and a remedial system is designed to meet these objectives, the next step is to design a monitoring program that will evaluate the success of the remedial system. The monitoring criteria will be important in establishing the required monitoring program. Water quality monitoring is important; water-level monitoring also is important and is less expensive and subject to less uncertainty.

The location of monitoring wells is critical to a successful monitoring program. For pump-and-treat technology, extraction and injection wells produce complex flow patterns locally, where previously there were different flow patterns (Keely, 1989). In Figure 14, for example, water moving along the flowline leading directly into an extraction well from upgradient moves most rapidly, whereas water at the lateral limits of the capture zone moves more slowly. The result is that certain parts of the aquifer are flushed rapidly while other parts are remediated relatively poorly. Another possibility is that previously clean portions of the aquifer may become contaminated. Thus, monitoring well locations should be based on an understanding of the flow system as it is modified by the pump-and-treat system. Modeling techniques, discussed previously, can be used to help in site-specific monitoring network design.

To determine the flow system generated by a pump-and-treat system, field evaluations must be made during the operational phase. Consequently, in addition to data collection for site characterization, data need to be collected during and after pump-and-treat system operation. Post-operational monitoring is needed to ensure that desorption or dissolution of residuals does not cause an increase in the level of contamination after operation of the system has ceased. This monitoring may be required for about two to five years after system termination and will depend on site conditions.

Evaluation and modification of existing pump-and-treat systems

Because of the uncertainties involved in subsurface characterization, a pump-and-treat system may require modification during the initial operational stages. Modifications may result from improved estimates of hydraulic conductivity or more complete information on chemistry and loading to the treatment facility. Other modifications may be due to mechanical failures of pumps, wells, or surface plumbing.

A similar situation to that involving a low-permeability zone may arise where a zone of contamination is not recovered by advection due to that zone's hydrodynamic isolation. That is, the complex flow patterns established by a pump-and-treat technology result in what are referred to in hydrodynamics as "stagnation zones." Movement of contaminants out of these zones is similar to the movement out of lower hydraulic conductivity zones. Fortunately, this situation is corrected by adjusting pumping rates and/or well locations.

Periodic review and modification of the design, construction, maintenance, and operation of the pump-and-treat system will probably be necessary. The performance of the system should be evaluated annually, or more frequently, to determine if the goals and standards of the design criteria are being met. If it is not, adjustment or modification of the system may be necessary. Modifications may also be made as one part of the contaminant plume becomes clean or when portions are not showing the desired progress. Adjustments or modifications can include relocating or adding extraction wells or altering pumping rates.

Switching from continuous pumping to pulsed pumping is one modification that may improve the efficiency of contaminant recovery. Pulsed pumping is the intermittent operation of a pump-and-treat system. As shown in Figure 15, the time when the pumps are off can allow the

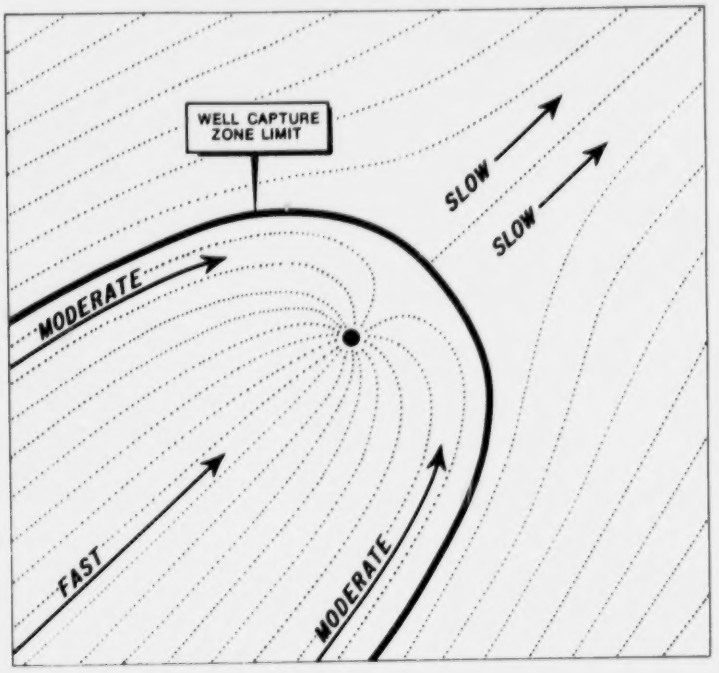

Figure 14. Flowline pattern generated by an extraction well (from Keely, 1989).

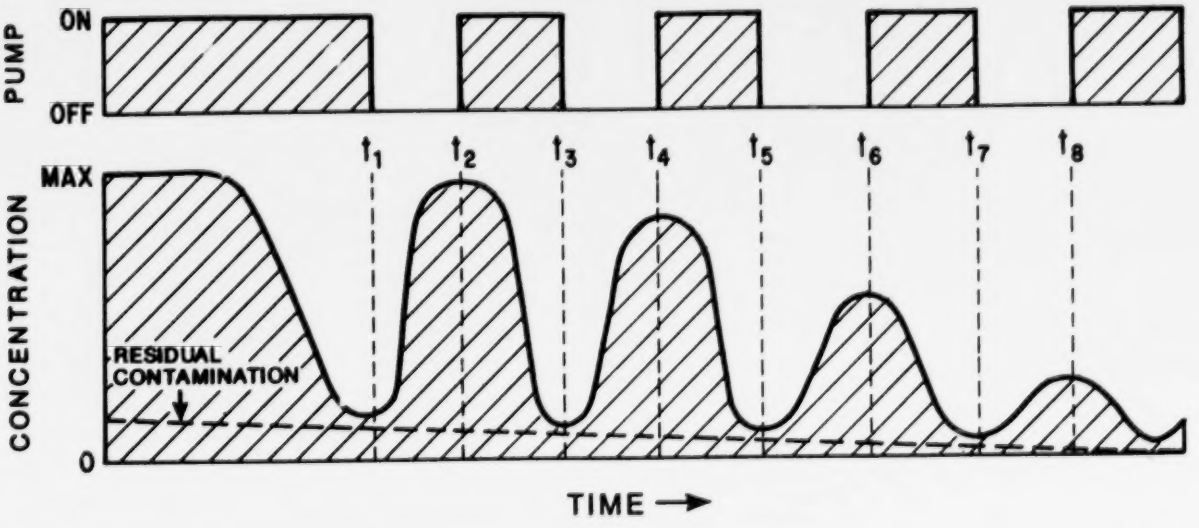

Figure 15. Reduction of residual contaminant mass by pulsed pumping (from Keely, 1989).

contaminants to diffuse out of less permeable zones and into adjacent higher hydraulic conductivity zones until maximum concentrations are achieved in the latter. For sorbed contaminants and residual NAPLs, this nonpumping period can allow sufficient time for equilibrium concentrations to be reached in local ground water. During the subsequent pumping cycle, the minimum volume of contaminated ground water can be removed at the maximum possible concentration for the most efficient treatment. The durations of pumping and nonpumping periods (about 1-30 days) are site specific and can only be optimized through trial-and-error operation. By occasionally cycling only select wells, possible stagnation (zero or low flow) zones may be brought into active flowpaths and remediated (Keely, 1989). If plume capture must be maintained, it will be necessary to maintain pumping on the plume boundaries and perhaps only use pulsed pumping on the interior of the plume. Termination of the pump-and-treat system occurs when the cleanup goals are met. In addition to meeting concentration goals, termination also may occur when optimum mass removal is achieved and it is not practical to reduce contaminant levels further.

References

Abriola, L.M., 1983. Mathematical modeling of the multiphase migration of organic compounds in a porous medium, Ph.D. Dissertation, Department of Civil Engineering, Princeton University, September.

Acker III, W.L., 1974. Basic Procedures for Soil Sampling and Core Drilling, Acker Drill Co., Inc., Scranton, Pennsylvania.

American Petroleum Institute, 1980. Underground spill cleanup manual, API Publication 1628, Washington,D.C.

American Petroleum Institute, 1989. A guide to the assessment and remediation of underground petroleum releases, API Publication 1628, (second edition), 81 pp., Washington, D.C.

Ball, J.W., E.A. Jenne, and D.K. Nordstrom, 1979. WATEQ2--A computerized chemical model for trace and major element speciation and mineral equilibria of natural waters, ACS Symp. Ser., 83, pp 815-835.

Benjamin, J.R., and C.A. Cornell, 1970. Probability Statistics and Decisions for Civil Engineers, McGraw-Hill, New York.

Bentall, R., 1963. Methods of determining permeability, transmissibility and drawdown, U.S. Geological Survey, Water Supply Paper, 1536-I, pp 243-341.

Barcelona, M.J., J.P. Gibb, and R.A. Miller, 1983. A guide to the selection of materials for monitoring well construction and ground-water sampling, Illinois State Water Survey Contract Report No. 327, USEPA-RSKERL, EPA-600/52-84/024, U.S. Environmental Protection Agency.

Barcelona, M.J., J.P. Gibb, J.A. Helfrich, and E.E. Garske, 1985. Practical guide for ground-water sampling, Illinois State Water Survey Contract Report No. 374, USEPA-RSKERL under cooperative agreement CR-809966-01, U.S. Environmental Protection Agency, Ada, Oklahoma.

Bouwer, E., J. Mercer, M. Kavanaugh, and F. DiGiano, 1988. Coping with groundwater contamination, Journal Water Pollution Control Federation, 6(8):1414-1428.

Bouwer, H. and R.C. Rice, 1976. A slug test for determining hydraulic conductivity of unconfined aquifers and completely or partially penetrating wells, Water Resources Research, 12:423-428.

Brown, R.A., G. Hoag, and R. Norris, 1988. The remediation game: pump, dig or treat? in Groundwater Quality Protection Pre-Conference Workshop Proceedings, Water Pollution Control Federation, 61st Annual Conference, Dallas, Texas, pp 207-240.

Bögli, A., 1980. Karst Hydrology and Physical Speleology, Springer-Verlag, New York, New York.

Campbell, M.D., and J.H. Lehr, 1973. Water Well Technology, McGraw-Hill Book Co., New York.

Cartwright, K., and J.M. Shafer, 1987. Selected technical considerations for data collection and interpretation--groundwater, in National Water Quality Monitoring and Assessment, Washington, D.C.

Cohen, R.M., R.R. Rabold, C.R. Faust, J.O. Rumbaugh, III, and J.R. Bridge, 1987. Investigation and hydraulic containment of chemical migration: Four landfills in Niagara Falls, Civil Engineering Practice, Journal of the Boston Society of Civil Engineers Section/ ASCE, 2(1):33-58.

Cooper, H.H., Jr., J.D. Bredehoeft, and S.S. Papadopulos, 1967. Response of a finite diameter well to an instantaneous charge of water, Water Resources Research, 3(1):263-269.

Cooper, R.M., and J.D. Istok, 1988a. Geostatistics applied to groundwater pollution. I: Methodology, Journal of Environmental Engineering, ASCE, 114(2).

Cooper, R.M., and J.D. Istok, 1988b. Geostatistics applied to groundwater contamination. II: Methodology, Journal of Environmental Engineering, ASCE, 114(2).

CRC Press, 1965. Handbook of Chemistry and Physics, 46th edition, Boca Raton, Florida.

Davis, J.C., 1973. Statistics and Data Analysis in Geology, John Wiley & Sons, New York, NY, 550 pp.

Davis, S.N., and R.J.M. DeWiest, 1966. Hydrogeology, John Wiley & Sons, New York, 463 pp.

de Pastrovich, T.L., Y. Baradat, R. Barthel, A. Chiarelli, and D.R. Fussell, 1979. Protection of groundwater from oil pollution,CONCAWE Report No. 3/79, Den Haag, Netherlands, 61 pp.

Dettinger, M.D., and J.L. Wilson, 1981. First-order analysis of uncertainty in numerical models of groundwater flow, I: Mathematical development, Water Resources Research, 17(1):149-161.

Dobrin, M.B., 1976. Introduction to Geophysical Prospecting, 3rd ed., McGraw-Hill, New York, 630 pp.

Driscoll, F.G., 1986. Ground Water and Wells (second edition), Johnson Division, UOP, Inc., St. Paul, Minnesota.

Electric Power Research Institute, 1989. Estimates of macrodispersivity based on analysis of hydraulic conductivity variability at the MADE site, EPRI EN-6405.

Englund, E., and A. Sparks, 1988. GEO-EAS (Geostatistical environmental assessment software) User's Guide, U.S. Environmental Protection Agency, EPA/600/4-88/033a, Las Vegas, Nevada.

Ferris, J.G., D.B. Knowles, R.H. Brown, and R.W. Stallman, 1962. Theory of aquifer tests, U.S. Geological Survey Water Supply Paper, 1536-E, pp 69-174.

Fetter, C.W. Jr., 1980. Applied Hydrogeology, Charles E. Merrill, Ohio.

Freeze, R.A., and J.A. Cherry, 1979. Groundwater, Prentice-Hall, Englewood Cliffs, New Jersey.

Fussell, D.R., H. Godjen, P. Hayward, R.H. Lilie, A. Marco, and C. Panisi, 1981. Revised inland oil spill clean-up manual, CONCAWE, Den Haag, Netherlands.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold Co., New York, 320 pp.

Gorelick, S.M., C.I. Voss, P.E. Gill, W. Murray, M.A. Saunders, and M.H. Wright, 1984. Aquifer reclamation design: The use of contaminant transport simulation combined with nonlinear programming, Water Resources Research, 20, pp 415-427.

Hall, C.W., 1988. Practical limits to pump and treat technology for aquifer remediation, in Groundwater Quality Protection Pre-Conference Workshop Proceedings, Water Pollution Control Federation, 61st Annual Conference, Dallas, Texas, pp 7-12.

Iman, R.L., and M. Shortencarier, 1984. A Fortran 77 program and user's guide for the generation of latin hypercube and random samples for use with computer models, Rep. NUREG/CR-3624, SAND83-2365, prepared for U.S. Nuclear Regulatory Commission by Sandia National Laboratory, Albuquerque, New Mexico.

International Association of Hydrological Sciences, 1988. Karst hydrogeology and karst environment protection, IAHS Publication 176, 1261 pp.

Jacob, C.E., 1950. Flow of groundwater in H. Rouse (ed.), Engineering Hydraulics, John Wiley & Sons, Inc., New York, pp 321-386.

Javandel, I., C. Doughty, and C.F. Tsang, 1984. Groundwater Transport: Handbook of Mathematical Models, American Geophysical Union, Water Resources Monograph 10, Washington, D.C, 228 pp.

Javandel, I., and C.F. Tsang, 1986. Capture-zone type curves: A tool for aquifer cleanup, Ground Water, 24(5):616-625.

Journal, A., 1978. Mining Geostatistics, Academic Press, London, England.

Kalos, M.H., and P.A. Whitlock, 1986. Monte Carlo Methods, Volume I: Basics, John Wiley & Sons, New York, 186 pp.

Keeley, J.W., D.C. Bouchard, M.R. Scalf, and C.G. Enfield, 1989. Practical limits to pump and treat technology for aquifer remediation. Submitted to Ground Water Monitoring Review.

Keely, J.F., 1984. Optimizing pumping strategies for contaminant studies and remedial actions, Ground Water Monitoring Review, 4(3):63-74.

Keely, J.F., 1989. Performance evaluations of pump-and-treat remediations EPA Superfund Ground Water Issue, EPA/540/4-89/005.

Keys, W.S., and L.M. MacCary, 1971. Application of borehole geophysics to water-resources investigations in Techniques of Water-Resources Investigations, U.S. Geological Survey, Book 2, Chapter E1.

Knox, R.C., L.W. Canter, D.F. Kincannon, E.L. Stover, and C.H. Ward, 1986. Aquifer Restoration: State of the Art, Noyes Publications, Park Ridge, New Jersey.

Kruseman, G.P. and N.A. De Ridder,1976. Analysis and evaluation of pumping test data, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 200 pp.

Kwader, T., 1986. The use of geophysical logs for determining formation water quality, Ground Water, 24, pp 11-15.

Lattman, L.H., and R.R. Parizek, 1964. Relationship between fracture traces and the occurrence of ground water in carbonate rocks, Journal of Hydrology, 2, pp 73-91.

Lin, C., G.F. Pinder, and E.F. Wood, 1982. Water and trichlorethylene as immiscible fluids in porous media, Water Resources Progress Report 83-W2-2, Princeton University, October.

Lindorff, D.E., and K. Cartwright, 1977. Ground-water contamination: Problems and remedial actions, Environmental Geology Notes No. 81, Illinois State Geological Survey, Urbana, Illinois, 58 pp.

Lyman, W.J., W.F. Reehl, and D.H. Rosenblatt (eds.), 1982. Handbook of Chemical Property Estimation Methods, McGraw-Hill Co., New York.

Mackay, D.M., and J.A. Cherry, 1989. Groundwater contamination: Pump-and-treat remediation, Environmental Science Technology, 23(6):630-636.

Marrin, D.L., and G.M. Thompson, 1984. Remote detection of volatile organic contaminants in groundwater via shallow soil gas sampling in Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Water Well Association, Worthington, Ohio, pp 172-187.

McDonald, M.G., and A.W. Harbaugh, 1984. A modular three-dimensional finite-difference groundwater flow model, U.S. Geological Survey, Open File Report 83-875.

Mercer, J.W., C.R. Faust, A.D. Truschel, and R.M. Cohen, 1987. Control of groundwater contamination: Case studies, Proceedings of Detection, Control and Renovation of Contaminated Ground Water, EE Div/ASCE, Atlantic City, pp. 121-133.

Morel, F., and J. Morgan, 1972. A numerical method for computing equilibria in aqueous chemical systems, Environmental Science Technology, 6, pp 58-67.

Papadopulos, I.S., J.D. Bredehoeft, and H.H. Cooper, Jr., 1973. On the analysis of "slug test" data, Water Resources Research, 9(4):1087-1089.

Quinlan, J.F., and R.O. Ewers, 1985. Ground water flow in limestone terrains: Strategy rationale and procedure for reliable, efficient monitoring of ground water quality in karst areas, Proceedings of the National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring (5th), Columbus, Ohio, National Water Well Association, Dublin, Ohio, pp 197-234.

Satkin, R.L., and P.B. Bedient, 1988. Effectiveness of various aquifer restoration schemes under variable hydrogeologic conditions, Ground Water, 26(4):488-498.

Scalf, M.R., S.F. McNabb, W.I. Dunlap, R.L. Cosby, and J. Fryberger, 1981. Manual of groundwater quality sampling procedures, Robert S. Kerr Environmental Research Laboratory, U.S. EPA, Ada, Oklahoma.

Shafer, J.M., 1987. GWPATH: Interactive ground-water flow path analysis, ISWS/BUL-69/87, Illinois State Water Survey, Champaign, Illinois.

Shah, D.O. (ed.), 1981. Surface Phenomena in Enhanced Oil Recovery, Plenum Press, New York.

Stewart, M., M. Layton, and T. Lizanec, 1983. Application of surface resistivity surveys to regional hydrogeologic reconnaissance, Ground Water, 21, pp 42-48.

Streltsova, T.D., 1988. Well Testing in Heterogeneous Formations, John Wiley & Sons, New York.

Sundstrom, D.W., and H.E. Klei, 1979. Wastewater Treatment, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 444 pp.

U.S. Environmental Protection Agency, 1984a. Case studies 1-23: Remedial response at hazardous waste sites, EPA/540/2-84-002b, Cincinnati, Ohio.

U.S. Environmental Protection Agency, 1984b. Summary report: Remedial response at hazardous waste sites, EPA/540/2-84-002a, Cincinnati, Ohio.

U.S. Environmental Protection Agency, 1985. Modeling remedial actions at uncontrolled hazardous waste sites, EPA/540/2-85/001, Cincinnati, Ohio.

U.S. Environmental Protection Agency, 1986a. RCRA ground-water monitoring technical enforcement guidance document, OSWER-9950.1, Washington, D.C.

U.S. Environmental Protection Agency, 1986b. Superfund public health evaluation manual, EPA/540/1-86/060, Washington, D.C.

U.S. Environmental Protection Agency, 1987a. A compendium of technologies used in the treatment of hazardous wastes, EPA/625/8-87/014, 49 pp.

U.S. Environmental Protection Agency, 1987b. Handbook Ground Water, EPA/625/6-87/016, Cincinnati, Ohio, 212 pp.

U.S. Environmental Protection Agency, 1987b. MINTEQA1, an equilibrium metal speciation model: user's manual, EPA/600/3-87/012, Athens, Georgia.

U.S. Environmental Protection Agency, 1988a. Guidance on remedial actions for contaminated ground water at Superfund sites. EPA/540/G-88/003.

U.S. Environmental Protection Agency, 1988b. Guidance for conducting remedial investigations and feasibility studies under CERCLA, March Draft, Office of Solid Waste and Engineering Response Directive 9355.3-01.

U.S. Environmental Protection Agency, 1988c. Groundwater modeling: an overview and status report. EPA/600/2-89/028.

U.S. Environmental Protection Agency, 1989. Evaluation of ground-water extraction remedies, Vols 1 and 2 (Draft), Prepared by CH2M Hill, Contract No. 68-W8-0098, Washington, D.C.

van der Heijde, P.K.M., Y. Bachmat, J. Bredehoeft, B. Andrews, D. Holtz, and S. Sebastian, 1985. Groundwater Management: The Use of Numerical Models, 2nd edition, AGU Water Resources Monograph no. 5, American Geophysical Union, Washington, D.C.

Walton, W.C., 1970. Groundwater Resource Evaluation, McGraw-Hill Book Co., New York.

Ward, D.S., D.R. Buss, J.W. Mercer, and S.S. Hughes, 1987. Evaluation of a groundwater corrective action of the Chem-Dyne Hazardous Waste site using a telescopic mesh refinement modeling approach, Water Resources Research, 23(4):603-617.

Wilson, L.G., 1981. Monitoring in the vadose zone, part I: Storage changes, Ground Water Monitoring Review, 1(3):32.

Wilson, L.G., 1982. Monitoring in the vadose zone, part II, Ground Water Monitoring Review, 2(4):31.

Wilson, L.G., 1983. Monitoring in the vadose zone, part III, Ground Water Monitoring Review, 3(4):155.

Wolery, T.J., 1979. Calculation of Chemical Equilibrium between Aqueous Solution and Minerals: The EQ3/6 Software Package, UCRL-52658, Lawrence Livermore Laboratories, Livermore, California.

Ziegler, G.J., 1989. Remediation through groundwater recovery and treatment, Pollution Engineering, July, pp 75-79.

Glossary

Adsorption:	Adherence of ions or molecules in solution to the surface of solids.
Advection:	The process whereby solutes are transported by the bulk mass of flowing fluid.
Aquifer:	A geologic unit that contains sufficient saturated permeable material to transmit significant quantities of water.
Aquifer test:	See pump test and slug test.
Biodegradation:	A subset of biotransformation, it is the biologically mediated conversion of a compound to more simple products.
Biotransformation:	Chemical alteration of organic compounds brought about by microorganisms.
Bulk density:	The oven-dried mass of a sample divided its field volume.
Confined aquifer:	An aquifer bounded above and below by units of distinctly lower hydraulic conductivity and in which the pore water pressure is greater than atmospheric pressure.
Conservative solutes:	Chemicals that do not react with the soil and/or native ground water or undergo biological, chemical, or radioactive decay.
Darcy's Law:	An empirical law stating that the velocity of flow through a porous medium is directly proportional to the hydraulic gradient assuming that the flow is laminar and inertia can be neglected.
Density:	The mass per unit volume of a substance.
Desorption:	The reverse of sorption.
Diffusion:	Mass transfer as a result of random motion of molecules; described by Fick's first law.
Dispersion:	Spreading and mixing chemical constituents in ground water caused by diffusion and mixing due to microscopic variations in velocities within and between pores.
Distribution coefficient:	The quantity of the solute, chemical, or radionuclide sorbed by the solid per unit weight of solid divided by the quantity dissolved in the water per unit volume of water.
DNAPL:	Denser-than-water nonaqueous phase liquid.
Effective porosity:	The ratio, usually expressed as a percentage, of the total volume of voids available for fluid transmission to the total volume of the porous medium.
EOR:	Enhanced oil recovery methods used to reduce interfacial tension by some type of injection.
Extraction well:	Pumped well used to remove contaminated ground water.
Fixation:	Mixing of contaminated soils with a chemical stabilizer, usually a cementatious grout compound.
Fracture trace:	Visible on aerial photographs, fracture traces are natural linear-drainage, soil-tonal, and topographic alignments that are probably the surface manifestation of underlying zones of fractures.
FS:	Feasibility study.
Heterogeneous:	A geologic unit in which the hydrologic properties vary from point to point.

Homogeneous:	A geologic unit in which the hydrologic properties are identical everywhere.
Hydraulic barrier:	Barrier to flow caused by system hydraulics, e.g., a line of ground-water discharge caused by extraction wells.
Hydraulic conductivity:	A measure of the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area of medium measured at right angles to the direction of flow.
Hydraulic gradient:	The change in head per unit distance in a given direction, typically in the principal flow direction.
Interstitial velocity:	Rate of discharge of ground water per unit area of the geologic medium per percentage volume of the medium occupied by voids measured at right angles to the direction of flow.
Intrinsic permeability:	A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. Intrinsic permeability is a property of the medium alone that is decendent on the shape and size of the openings through which the liquid moves.
Linear soil partition coefficient:	Ratio of the mass concentration of a solute in solid phase to its mass concentration in the aqueous phase.
LNAPL:	Lighter-than-water nonaqueous phase liquid.
Miscible:	Able to be mixed.
MCL:	Maximum contaminant level: Enforceable standards established under the Safe Drinking Water Act.
MCLG:	Maximum contaminant level goal: Non-enforceable health goals established under the Safe Drinking Water Act intended to protect against known and anticipated adverse human health effects with an adequate margin of safety.
Monitoring well:	A tube or pipe, open to the atmosphere at the top and to water at the bottom, usually along an interval of slotted screen, used for taking ground-water samples.
NAPL:	Nonaqueous phase liquids.
Partitioning:	Chemical equilibrium condition where a chemical's concentration is apportioned between two different phases according to the partition coefficient, which is the ratio of a chemical's concentration in one phase to its concentration in the other phase.
Piezometer:	A tube or pipe, open to the atmosphere at the top and to water at the bottom, and sealed along its length, used to measure the hydraulic head in a geologic unit.
Porosity:	A measure of interstitial space contained in a rock (or soil) expressed as the percentage ratio of void space to the total (gross) volume of the rock.
Pulsed pumping:	Pump-and-treat enhancement where extraction wells are periodically not pumped to allow concentrations in the extracted water to increase.
Pump test:	Test for estimating the values of various hydrogeologic parameters in which water is continuously pumped from a well and the consequent effect on water levels in surrounding piezometers or monitoring wells is monitored.
Remedial action objective:	A description of remedial goals for each medium of concern at a site; expressed in terms of the contamination of concern, exposure route(s) and receptor(s), and maximum acceptable exposure level(s).
Residual saturation:	Saturation below which fluid drainage will not occur.

Retardation:	The movement of a solute through a geologic medium at a velocity less than that of the flowing ground water due to sorption or other removal of the solute.
RI:	Remedial investigation.
Slug test:	A test for estimating hydraulic conductivity values in which a rapid water-level change is produced in a piezometer or monitoring well, usually by introducing or withdrawing a "slug" of water or a weight. The resultant rise or decline in the water level is monitored.
Soil gas survey:	Technique used to obtain air from subsurface cavities (e.g., using a soil gas probe); soil gas sample is analyzed and used as an indicator of volatile organic compounds in ground water or soil.
Sorption:	Processes that remove solutes from the fluid phase and concentrate them on the solid phase of a medium.
Specific gravity:	The ratio of a substance's density to the density of some standard substance, usually water.
Storage coefficient:	The volume of water an aquifer releases from, or takes into, storage per unit surface area of aquifer per unit change in the component of head normal to that surface.
Superposition:	Principle used for linear problems, such as confined ground-water flow, that allows equation solutions to be added to form new solutions. For example, if within a well field, pumping rates of the pumped wells are known, the composite drawdown at a point can be determined by summing the drawdown caused by each individual pumped well.
Tailing:	The slow, nearly asymptotic decrease in contaminant concentration in water flushed through contaminated geologic material.
Treatment train:	Combination of several remedial actions, e.g., pump-and-treat approach used for ground-water contamination, combined with vacuum extraction for soil contamination.
Vacuum extraction:	Inducing advective-vapor transport by withdrawing or injecting air through wells screened in the vadose zone.
Vadose zone:	That region above the saturated zone.
Viscosity:	The internal friction within a fluid that causes it to resist flow.
Volatilization:	The transfer of a chemical from liquid to the gas phase.
Water table:	The surface in an aquifer at which pore water pressure is equal to atmospheric pressure.
Water-table aquifer:	An aquifer in which the water table forms the upper boundary.
Zone of capture:	Area surrounding a pumping well that encompasses all areas or features that supply ground-water recharge to the well.
Zone of influence:	Area surrounding a pumping or recharging well within which the water table or potentiometric surface has been changed due to the well's pumping or recharge.

Appendix A - Chemical Data

Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
PESTICIDES												
Acrolein [2-Propenal]	107-02-8	PP	2.08E+05	H	2.69E+02	H	9.54E-05	X			8.13E-01	H
Aldicarb [Temik]	116-06-3		7.80E+03	E							5.00E+00	F
Aldrin	309-00-2	HPP	1.80E-01	A	6.00E-06	A	1.60E-05	A	9.60E+04	A	2.00E+05	A
Captan	133-06-2		5.00E-01	A	6.00E-05	A	4.75E-05	A	6.40E+03	B	2.24E+02	A
Carbaryl [Sevin]	63-25-2		4.00E+01	A	5.00E-03	A	3.31E-05	X	2.30E+02	G	2.29E+02	A
Carbofuran	1563-66-2		4.15E+02	G	2.00E-05	G	1.40E-08	X	2.94E+01	F	2.07E+02	F
Carbophenothion [Trithion]	786-19-6								4.66E+04	F		
Chlordane	57-74-9	HPP	5.60E-01	A	1.00E-05	A	9.63E-06	A	1.40E+05	A	2.09E+03	A
p-Chloroaniline [4-Chlorobenzenamine]	106-47-8	HSL	5.30E+03	L	2.00E-02	G	6.40E-07	X	5.61E+02	F	6.76E+01	H
Chlorobenzilate	510-15-6		2.19E+01	A	1.20E-06	A	2.34E-08	A	8.00E+02	B	3.24E+04	A
Chlorpyrifos [Dursban]	2921-88-2		3.00E-01	E	1.87E-05	J	2.87E-05	X	1.36E+04	E	6.60E+04	F
Crotoxyphos [Ciodrin]	7700-17-6		1.00E+03	E	1.40E-05	J	5.79E-09	X	7.48E+01	F		
Cyclophosphamide	50-18-0		1.31E+09	A					4.20E-02	B	6.03E-04	A
DDD	72-54-8	HPP	1.00E-01	A	1.89E-06	A	7.96E-06	A	7.70E+05	A	1.58E+06	A
DDE	72-55-9	HPP	4.00E-02	A	6.50E-06	A	6.80E-05	A	4.40E+06	A	1.00E+07	A
DDT	50-29-3	HPP	5.00E-03	A	5.50E-06	A	5.13E-04	A	2.43E+05	A	1.55E+06	A
Diazonin [Spectracide]	333-41-5		4.00E+01	E	1.40E-04	J	1.40E-06	X	8.50E+01	P	1.05E+03	F
1,2-Dibromo-3-chloropropane [DBCP]	96-12-8		1.00E+03	A	1.00E+00	A	3.11E-04	A	9.80E+01	B	1.95E+02	A
1,2-Dichloropropane	78-87-5	HPP	2.70E+03	A	4.20E+01	A	2.31E-03	A	5.10E+01	A	1.00E+02	A
1,3-Dichloropropene [Telone]	542-75-6	HPP	2.80E+03	A	2.50E+01	A	1.30E-01	A	4.80E+01	A	1.00E+02	A
Dichlorvos	62-73-7		1.00E+04	E	1.20E-02	J	3.50E-07	X			2.50E+01	E
Dieldrin	60-57-1	HPP	1.95E-01	A	1.78E-07	A	4.58E-07	A	1.70E+03	A	3.16E+03	A
Dimethoate	60-51-5		2.50E+04	A	2.50E-02	A	3.00E-07	X			5.10E-01	E
Dinoseb	88-85-7		5.00E+01	A	5.00E-05	G	3.16E-07	X	1.24E+02	E	1.98E+02	F
N,N-Diphenylamine	122-39-4		5.76E+01	A	3.80E-05	A	1.47E-07	A	4.70E+02	B	3.98E+03	A
Disulfoton	298-04-4		2.50E+01	E	1.80E-04	E	2.60E-06	X	1.60E+03	F		
alpha-Endosulfan	115-29-7	HPP	1.60E-01	H	1.00E-05	H	3.35E-05	X			3.55E+03	H
beta-Endosulfan	115-29-7	HPP	7.00E-02	H	1.00E-05	H	7.65E-05	X			4.17E+03	H
Endosulfan Sulfate	1031-07-8	HPP	1.60E-01	H							4.57E+03	H
Endrin	72-20-8	HPP	2.40E-02	E	2.00E-07	G	4.17E-06	X			2.18E+05	E
Endrin Aldehyde	7421-93-4	PP										
Endrin Ketone		HSL										
Ethion	563-12-2		2.00E+00	E	1.50E-06	J	3.79E-07	X	1.54E+04	E		
Ethylene Oxide	75-21-8		1.00E+06	A	1.31E+03	A	7.56E-05	A	2.20E+00	B	6.03E-01	A
Fenitrothion	122-14-5		3.00E+01	E	6.00E-06	J	7.30E-08	X			2.40E+03	E
Heptachlor	76-44-8	HPP	1.80E-01	A	3.00E-04	A	8.19E-04	A	1.20E-04	A	2.51E+04	A
Heptachlor Epoxide	1024-57-3	HPP	3.50E-01	A	3.00E-04	A	4.39E-04	A	2.20E+02	A	5.01E+02	A
alpha-Hexachlorocyclohexane	319-84-6	HPP	1.63E+00	A	2.50E-05	A	5.87E-06	A	3.80E+03	A	7.94E+03	A

Notes: PP = Priority Pollutant; HSL = Hazardous Substance List Parameter; HPP = PP and HSL Parameters.
Additional notes and data references are provided at end of this table.

Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
beta-Hexachlorocyclohexane	319-85-7	HPP	2.40E-01	A	2.80E-07	A	4.47E-07	A	3.80E+03	A	7.94E+03	A
delta-Hexachlorocyclohexane	319-86-8	HPP	3.14E+01	A	1.70E-05	A	2.07E-07	A	6.60E+03	A	1.26E+04	A
gamma-Hexachlorocyclohexane [Lindane]	58-89-9	HPP	7.80E+00	A	1.60E-04	A	7.85E-06	A	1.08E+03	A	7.94E+03	A
Isophorone	78-59-1	HPP	1.20E+04	H	3.80E-01	H	5.75E-06	X			5.01E+01	H
Kepone	143-50-0		9.90E-03	A					5.50E+04	B	1.00E+02	A
Leptophos	21609-90-5		2.40E+00	E					9.30E+03	E	2.02E+06	E
Malathion	121-75-7		1.45E+02	A	4.00E-05	A	1.20E-07	X	1.80E+03	F	7.76E+02	A
Methoxychlor	72-43-5	HSL	3.00E-03	E					8.00E+04	E	4.75E+04	E
Methyl Parathion	298-00-0		6.00E+01	A	9.70E-06	A	5.59E-08	A	5.10E+03	F	8.13E+01	A
Mirex [Dechlorane]	2385-85-5		6.00E-01	C	3.00E-01	C	3.59E-01	X	2.40E+07	G	7.80E+06	D
Nitralin	4726-14-1		6.00E-01	E	9.30E-09	J	7.04E-09	X	9.60E+02	G		
Parathion	56-38-2		2.40E+01	G	3.78E-05	J	6.04E-07	X	1.07E+04	F	6.45E+03	F
Phenylurea [Phenylcarbamide]	64-10-8								7.63E+01	F	6.61E+00	M
Phorate [Thimet]	298-02-2		5.00E+01	E	8.40E-04	J	8.49E-11	X	3.26E+03	F		
Phosmet	732-11-6		2.50E+01	E	<1.0E-03	J					6.77E+02	E
Ronnel [Fenchlorphos]	299-84-3		6.00E+00	E	8.00E-04	J	5.64E-05	X			4.64E+04	E
Strychnine	57-24-9		1.56E+02	A							8.51E+01	M
2,3,7,8-Tetrachlorodibenzo-p-dioxin	1746-01-6		2.00E-04	A	1.70E-06	A	3.60E-03	A	3.30E+06	A	5.25E+06	A
Toxaphene	8001-35-2	HPP	5.00E-01	A	4.00E-01	A	4.36E-01	A	9.64E+02	A	2.00E+03	A
Trichlorfon [Chlorofos]	52-68-6		1.54E+05	A	7.80E-06	A	1.71E-11	A	6.10E+00	B	1.95E+02	A
HERBICIDES												
Alachlor	15972-60-8		2.42E+02	E					1.90E+02	E	4.34E+02	F
Ametryn	834-12-8		1.85E+02	E					3.88E+02	F		
Amitrole [Aminotriazole]	61-82-5		2.80E+05	A					4.40E+00	B	8.32E-03	A
Atrazine	1912-24-9		3.30E+01	G	1.40E-06	K	2.59E-13	X	1.63E+02	F	2.12E+02	F
Benfluralin [Benefin]	1861-40-1		<1.0E+00	E	3.89E-04	J			1.07E+04	E		
Bromocil	314-40-9		8.20E+02	P					7.20E+01	F	1.04E+02	F
Cacodylic Acid	75-60-5		8.30E+05	A					2.40E+00	B	1.00E+00	A
Chloramben	133-90-4		7.00E+02	E	<7.0E-03	J			2.10E+01	E	1.30E+01	F
Chlorpropham	101-21-3		8.80E+01	E					8.16E+02	F	1.16E+03	F
Dalapon [2,2-Dichloropropanoic Acid]	75-99-0		5.02E+05	E							5.70E+00	F
Diallate	2303-16-4		1.40E+01	A	6.40E-03	A	1.65E-04	A	1.90E+03	G	5.37E+00	A
Dicamba	1918-00-9		4.50E+03	E	2.00E-05	G	1.30E-09	X	2.20E+00	F	3.00E+00	F
Dichlobenil [2,6-Dichlorobenzonitrile]	1194-65-6		1.80E+01	E	3.00E-06	J	3.77E-08	X	2.24E+02	F	7.87E+02	F
2,4-Dichlorophenoxyacetic Acid [2,4-D]	94-75-7		6.20E+02	A	4.00E-01	A	1.88E-04	A	1.96E+01	F	6.46E+02	A
Dipropetryne	47-51-7		1.60E+01	J	7.50E-07	J	1.53E-08	X	1.18E+03	F		
Diuron	330-54-1		4.20E+01	E	<3.1E-06	J			3.82E+02	F	6.50E+02	F
Fenuron	101-42-8		3.85E+03	E	<1.6E-04	K			4.22E+01	F	1.00E+01	E
Fluometuron	2164-17-2		9.00E+01	G					1.75E+02	G	2.20E+01	E

Notes: PP = Priority Pollutant; HSL = Hazardous Substance List Parameter; HPP = PP and HSL Parameters.
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Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
Linuron	330-55-2		7.50E+01	E	1.50E-05	J	6.56E-08	X	8.63E+02	F	1.54E+02	E
Methazole [Oxydiazol]	20354-26-1		1.50E+00	E					2.62E+03	E		
Metobromuron	3060-89-7		3.30E+02	E	3.00E-06	J	3.10E-09	X	2.71E+02	F		
Monuron	150-68-5		2.30E+02	E	5.00E-07	J	5.68E-10	X	1.83E+02	F	1.33E+02	F
Neburon	555-37-3		4.80E+00	E					3.11E+03	F		
Oxadiazon	19666-30-9		7.00E-01	E	<1.0E-06	J			3.24E+03	E		
Paraquat	4685-14-7		1.00E+06	E					1.55E+04	E	1.00E+00	F
Phenylmercuric Acetate [PMA]	62-38-4		1.67E+03	A								
Picloram	1918-02-1		4.30E+02	E	<6.2E-07	K			2.55E+01	F	2.00E+00	F
Prometryne	7287-19-6		4.80E+01	E	1.00E-06	J	6.62E-09	X	6.14E+02	F		
Propachlor	1918-16-7		5.80E+02	E					2.65E+02	E	5.60E+02	E
Propazine	139-40-2		8.60E+00	E	1.60E-07	K	5.63E-09	X	1.53E+02	F	7.85E+02	E
Silvex [Fenoprop]	93-72-1		1.40E+02	E					2.60E+03	E		
Simazine	122-34-9		3.50E+00	E	3.60E-08	K	2.73E-09	X	1.38E+02	F	8.80E+01	F
Terbacil	5902-51-2		7.10E+02	E					4.12E+01	F	7.80E+01	F
2,4,5-Trichlorophenoxyacetic Acid	93-76-5		2.38E+02	E					8.01E+01	F	4.00E+00	E
Triclopyr	55335-06-3		4.30E+02	E	1.26E-06	J	9.89E-10	X	2.70E+01	E	3.00E+00	E
Trifluralin	1582-09-8		6.00E-01	E	2.00E-04	G	1.47E-04	X	1.37E+04	E	2.20E+05	E
ALIPHATIC COMPOUNDS												
Acetonitrile [Methyl Cyanide]	75-05-8		infinite	A	7.40E+01	A	4.00E-06	A	2.20E+00	B	4.57E-01	A
Acrylonitrile [2-Propenenitrile]	107-13-1	PP	7.94E+04	A	1.00E+02	A	8.84E-05	A	8.50E-01	A	1.78E+00	A
Bis(2-chloroethoxy)methane	111-91-1	HPP	8.10E+04	I	<1.0E-01	I					1.82E+01	I
Bromodichloromethane [Dichlorobromometh]	75-27-4	HPP	4.40E+03	Q	5.00E+01	H	2.40E-03	Q	6.10E+01	Q	7.59E+01	I
Bromomethane [Methyl Bromide]	74-83-9	HPP	1.30E+04	G	1.40E+03	G	1.30E-02	G			1.26E+01	I
1,3-Butadiene	106-99-0		7.35E+02	A	1.84E-03	A	1.78E-01	A	1.20E+02	B	9.77E+01	A
Chloroethane [Ethyl Chloride]	75-00-3	HPP	5.74E+03	C	1.00E+03	C	6.15E-04	X	1.70E+01	C	3.50E+01	C
Chloroethene [Vinyl Chloride]	75-01-4	HPP	2.67E+03	A	2.66E+03	A	8.19E-02	A	5.70E+01	B	2.40E+01	A
Chloromethane [Methyl Chloride]	74-87-3	HPP	6.50E+03	A	4.31E+03	A	4.40E 02	A	3.50E+01	B	9.50E-01	A
Cyanogen [Ethanedinitrile]	460-19-5		2.50E+05	A								
Dibromochloromethane	124-48-1	HPP	4.00E+03	Q	1.50E+01	A	9.90E-04	Q	8.40E+01	Q	1.23E+02	A
Dichlorodifluoromethane [Freon 12]	75-71-8		2.80E+02	A	4.87E+03	A	2.97E+00	X	5.80E+01	A	1.45E+02	A
1,1-Dichloroethane [Ethylidine Chloride]	75-34-3	HPP	5.50E+03	A	1.82E+02	A	4.31E-03	A	3.00E+01	A	6.17E+01	A
1,2-Dichloroethane [Ethylene Dichloride]	107-06-2	HPP	8.52E+03	A	6.40E+01	A	9.78E-04	A	1.40E+01	A	3.02E+01	A
1,1-Dichloroethene [Vinylidine Chloride]	75-35-4	HPP	2.25E+03	A	6.00E+02	A	3.40E-02	A	6.50E+01	A	6.92E+01	A
1,2-Dichloroethene (cis)	540-59-0		3.50E+03	A	2.08E+02	A	7.58E-03	A	4.90E+01	B	5.01E+00	A
1,2-Dichloroethene (trans)	540-59-0	HPP	6.30E+03	A	3.24E+02	A	6.56E-03	A	5.90E+01	A	3.02E+00	A
Dichloromethane [Methylene Chloride]	75-09-2	HPP	2.00E+04	A	3.62E+02	A	2.03E-03	A	8.80E+00	A	2.00E+01	A
Ethylene Dibromide [EDB]	106-93-4		4.30E+03	A	1.17E+01	A	6.73E-04	A	4.40E+01	A	5.75E+01	A
Hexachlorobutadiene	87-68-3	HPP	1.50E-01	A	2.00E+00	A	4.57E+00	A	2.90E+04	A	6.02E+04	A

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Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
Hexachlorocyclopentadiene	77-47-4	HPP	2.10E+00	A	8.00E-02	A	1.37E-02	A	4.80E+03	A	1.10E+05	A
Hexachloroethane [Perchloroethane]	67-72-1	HPP	5.00E+01	A	4.00E-01	A	2.49E-03	A	2.00E+04	A	3.98E+04	A
Iodomethane [Methyl Iodide]	77-88-4		1.40E+04	A	4.00E+02	A	5.34E-03	A	2.30E+01	B	4.90E+01	A
Isoprene	78-79-5				4.00E+02	A						
Pentachloroethane [Pentalin]	76-01-7		3.70E+01	C	3.40E+00	C	2.44E-02	X	1.90E+03	D	7.76E+02	C
1,1,1,2-Tetrachloroethane	630-20-6		2.90E+03	A	5.00E+00	A	3.81E-04	A	5.40E+01	B		
1,1,2,2-Tetrachloroethane	79-34-5	HPP	2.90E+03	A	5.00E+00	A	3.81E-04	A	1.18E+02	A	2.45E+02	A
Tetrachloroethene [PERC]	127-18-4	HPP	1.50E+02	A	1.78E+01	A	2.59E-02	A	3.64E+02	A	3.98E+02	A
Tetrachloromethane [CarbonTetrachloride]	56-23-5	HPP	7.57E+02	A	9.00E+01	A	2.41E-02	A	4.39E+02	Q	4.37E+02	A
Tribromomethane [Bromoform]	75-25-2	HPP	3.01E+03	A	5.00E+00	A	5.52E-04	A	1.16E+02	A	2.51E+02	A
1,1,1-Trichloroethane [Methylchloroform]	71-55-6	HPP	1.50E+03	A	1.23E+02	A	1.44E-02	A	1.52E+02	A	3.16E+02	A
1,1,2-Trichloroethane [Vinyltrichloride]	79-00-5	HPP	4.50E+03	A	3.00E+01	A	1.17E-03	A	5.60E+01	A	2.95E+02	A
Trichloroethene [TCE]	79-01-6	HPP	1.10E+03	A	5.79E+01	A	9.10E-03	A	1.26E+02	A	2.40E+02	A
Trichlorofluoromethane [Freon 11]	75-69-4	PP	1.10E+03	A	6.67E+02	A	1.10E-01	Q	1.59E+02	A	3.39E+02	A
Trichloromethane [Chloroform]	67-66-3	HPP	8.20E+03	A	1.51E+02	A	2.87E-03	A	4.70E+01	C	9.33E+01	A
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1		1.00E+01	A	2.70E+02	A					1.00E+02	A
AROMATIC COMPOUNDS												
1,1-Biphenyl [Diphenyl]	92-52-4		7.50E+00	E	6.00E-02	G	1.50E-03	G			7.54E+03	E
Benzene	71-43-2	HPP	1.75E+03	A	9.52E+01	A	5.59E-03	A	8.30E+01	A	1.32E+02	A
Bromobenzene [Phenyl Bromide]	108-86-1		4.46E+02	E	4.14E+00	O	1.92E-03	X	1.50E+02	P	9.00E+02	E
Chlorobenzene	108-90-7	HPP	4.66E+02	A	1.17E+01	A	3.72E-03	A	3.30E+02	Q	6.92E+02	A
4-Chloro-m-cresol [Chlorocresol]	59-50-7	HPP	3.85E+03	C	5.00E-02	C	2.44E-06	X	4.90E+02	C	9.80E+02	C
2-Chlorophenol [o-Chlorophenol]	95-57-8	HPP	2.90E+04	C	1.80E+00	C	1.05E-05	X	4.00E+02	C	1.45E+02	C
Chlorotoluene [Benzyl Chloride]	100-44-7		3.30E+03	A	1.00E+00	A	5.06E-05	A	5.00E+01	B	4.27E+02	A
m-Chlorotoluene	108-41-8		4.80E+01	D	4.60E+00	C	1.60E-02	X	1.20E+03	D	1.90E+03	C
o-Chlorotoluene	95-49-8		7.20E+01	C	2.70E+00	C	6.25E-03	X	1.60E+03	D	2.60E+03	C
p-Chlorotoluene	106-43-4		4.40E+01	D	4.50E+00	C	1.70E-02	X	1.20E+03	D	2.00E+03	C
Cresol (Technical) [Methylphenol]	1319-77-3		3.10E+04	A	2.40E-01	A	1.10E-06	A	5.00E+02	A	9.33E+01	A
o-Cresol [2-Methylphenol]	95-48-7	HSL	2.50E+04	J	2.43E-01	O	1.50E-06	X			8.91E+01	M
p-Cresol [4-Methylphenol]	106-44-5	HSL			1.14E-01	O					8.51E+01	M
Dibenzofuran		HSL									1.32E+04	M
1,2-Dichlorobenzene [o-Dichlorobenzene]	95-50-1	HPP	1.00E+02	A	1.00E+00	A	1.93E-03	A	1.70E+03	A	3.98E+03	A
1,3-Dichlorobenzene [m-Dichlorobenzene]	541-73-1	HPP	1.23E+02	A	2.28E+00	A	3.59E-03	A	1.70E+03	A	3.98E+03	A
1,4-Dichlorobenzene [p-Dichlorobenzene]	106-46-7	HPP	7.90E+01	A	1.18E+00	A	2.89E-03	A	1.70E+03	A	3.98E+03	A
2,4-Dichlorophenol	120-83-2	HPP	4.60E+03	A	5.90E-02	A	2.75E-06	A	3.80E+02	A	7.94E+02	A
Dichlorotoluene [Benzal Chloride]	98-87-3		2.50E+00	D	3.00E-01	C	2.54E-02	X	9.90E+03	D	1.60E+04	D
Diethylstilbestrol [DES]	56-53-1		9.60E-03	A					2.80E+01	B	2.88E+05	A
2,4-Dimethylphenol [as-m-Xylenol]	1300-71-6	HPP	4.20E+03	C	6.21E-02	H	2.38E-06	X	2.22E+02	C	2.63E+02	C
1,3-Dinitrobenzene	99-65-0		4.70E+02	A					1.50E+02	B	4.17E+01	A

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Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
4,6-Dinitro-o-cresol	534-52-1	HPP	2.90E+02	A	5.00E-02	A	4.49E-05	A	2.40E+02	A	5.01E+02	A
2,4-Dinitrophenol	51-28-5	HPP	5.60E+03	A	1.49E-05	A	6.45E-10	A	1.66E+01	A	3.16E+01	A
2,3-Dinitrotoluene	602-01-7		3.10E+03	A					5.30E+01	B	1.95E+02	A
2,4-Dinitrotoluene	121-14-2	HPP	2.40E+02	A	5.10E-03	A	5.09E-06	A	4.50E+01	A	1.00E+02	A
2,5-Dinitrotoluene	619-15-8		1.32E+03	A					8.40E+01	B	1.90E+02	A
2,6-Dinitrotoluene	606-20-2	HPP	1.32E+03	A	1.80E-02	A	3.27E-06	A	9.20E+01	A	1.00E+02	A
3,4-Dinitrotoluene	610-39-9		1.08E+03	A					9.40E+01	B	1.95E+02	A
Ethylbenzene [Phenylethane]	100-41-4	HPP	1.52E+02	A	7.00E+00	A	6.43E-03	A	1.10E+03	A	1.41E+03	A
Hexachlorobenzene [Perchlorobenzene]	118-74-1	HPP	6.00E-03	A	1.09E-05	A	6.81E-04	A	3.90E+03	A	1.70E+05	A
Hexachlorophene [Dermadex]	70-30-4		4.00E-03	A					9.10E+04	B	3.47E+07	A
Nitrobenzene	98-95-3	HPP	1.90E+03	A	1.50E-01	A	2.20E-05	G	3.60E+01	A	7.08E+01	A
2-Nitrophenol [o-Nitrophenol]	88-75-5	HPP	2.10E+03	H							5.75E+01	H
4-Nitrophenol [p-Nitrophenol]	100-07-7	HPP	1.60E+04	H							8.13E+01	H
m-Nitrotoluene [Methylnitrobenzene]	99-08-1		4.98E+02	G							2.92E+02	H
Pentachlorobenzene	608-93-5		1.35E-01	A	6.00E-03	C			1.30E+04	B	1.55E+05	A
Pentachloronitrobenzene [Quintozene]	82-68-8		7.11E-02	A	1.13E-04	A	6.18E-04	A	1.90E+04	B	2.82E+05	A
Pentachlorophenol	87-86-5	HPP	1.40E+01	A	1.10E-04	A	2.75E-06	A	5.30E+04	A	1.00E+05	A
Phenol	108-95-2	HPP	9.30E+04	A	3.41E-01	A	4.54E-07	A	1.42E+01	A	2.88E+01	A
Pyridine	110-86-1		1.00E+06	A	2.00E+01	A					4.57E+00	A
Styrene [Ethenylbenzene]	100-42-5	HSL	3.00E+02	R	4.50E+00	R	2.05E-03	X				
1,2,3,4-Tetrachlorobenzene	634-66-2		3.50E+00	C	4.00E-02	C			1.80E+04	D	2.88E+04	C
1,2,3,5-Tetrachlorobenzene			2.40E+00	C	7.00E-02	C			1.78E+04	D	2.88E+04	C
1,2,4,5-Tetrachlorobenzene	95-94-3		6.00E+00	A	5.40E-03	O			1.60E+03	B	4.68E+04	A
2,3,4,6-Tetrachlorophenol	58-90-2		7.00E+00	C	4.60E-03	C			9.80E+01	B	1.26E+04	A
Toluene [Methylbenzene]	108-88-3	HPP	5.35E+02	A	2.81E+01	A	6.37E-03	A	3.00E+02	A	5.37E+02	A
1,2,3-Trichlorobenzene	87-61-6		1.20E+01	C	2.10E-01	C	4.23E-03	X	7.40E+03	D	1.29E+04	C
1,2,4-Trichlorobenzene	120-82-1	HPP	3.00E+01	A	2.90E-01	A	2.31E-03	A	9.20E+03	A	2.00E+04	A
1,3,5-Trichlorobenzene	108-70-3		5.80E+00	C	5.80E-01	C	2.39E-02	X	6.20E+03	D	1.41E+04	C
2,4,5-Trichlorophenol	95-95-4	HSL	1.19E+03	A	1.00E+00	A	2.18E-04	A	8.90E+01	B	5.25E+03	A
2,4,6-Trichlorophenol	88-06-2	HPP	8.00E+02	A	1.20E-02	A	3.90E-06	A	2.00E+03	A	7.41E+03	A
1,2,4-Trimethylbenzene [Pseudocumene]	95-63-6		5.76E+01	G	2.03E+00	O	5.57E-03	X				
Xylene (mixed)	1330-20-7	HSL	1.98E+02	A	1.00E+01	A	7.04E-03	A	2.40E+02	B	1.83E+03	A
m-Xylene [1,3-Dimethylbenzene]	108-38-3		1.30E+02	A	1.00E+01	A	1.07E-02	X	9.82E+02	D	1.82E+03	A
o-Xylene [1,2-Dimethylbenzene]	95-47-6		1.75E+02	A	6.60E+00	G	5.10E-03	G	8.30E+02	D	8.91E+02	A
p-Xylene [1,4-Dimethylbenzene]	106-42-3		1.98E+02	A	1.00E+01	A	7.05E-03	X	8.70E+02	D	1.41E+03	A
POLYAROMATIC HYDROCARBONS												
Acenaphthylene	208-96-8	HPP	3.93E+00	A	2.90E-02	A	1.48E-03	A	2.50E+03	A	5.01E+03	A
Acenapthene	83-32-9	HPP	3.42E+00	A	1.55E-03	A	9.20E-05	A	4.60E+03	A	1.00E+04	A
Anthracene	120-12-7	HPP	4.50E-02	A	1.95E-04	A	1.02E-03	A	1.40E+04	A	2.82E+04	A

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Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
Benz(c)acridine	225-51-4		1.40E+01	A					1.00E+03	B	3.63E+04	A
Benzo(a)anthracene	56-55-3	HPP	5.70E-03	A	2.20E-08	A	1.16E-06	A	1.38E+06	A	3.98E+05	A
Benzo(a)pyrene	50-32-8	HPP	1.20E-03	A	5.60E-09	A	1.55E-06	A	5.50E+06	A	1.15E+06	A
Benzo(b)fluoranthene	205-99-2	HPP	1.40E-02	A	5.00E-07	A	1.19E-05	A	5.50E+05	A	1.15E+06	A
Benzo(ghi)perylene	191-24-2	HPP	7.00E-04	A	1.03E-10	A	5.34E-08	A	1.60E+06	A	3.24E+06	A
Benzo(k)fluoranthene	207-08-9	HPP	4.30E-03	A	5.10E-07	A	3.94E-05	A	5.50E+05	A	1.15E+06	A
2-Chloronapthalene	91-58-7	HPP	6.74E+00	I	1.70E-02	I	4.27E-04	X			1.32E+04	I
Chrysene	218-01-9	HPP	1.80E-03	A	6.30E-09	A	1.05E-06	A	2.00E+05	A	4.07E+05	A
1,2,7,8-Dibenzopyrene	189-55-9		1.01E-01	A					1.20E+03	B	4.17E+06	A
Dibenz(a,h)anthracene	53-70-3	HPP	5.00E-04	A	1.00E-10	A	7.33E-08	A	3.30E+06	A	6.31E+06	A
7,12-Dimethylbenz(a)anthracene	57-97-6		4.40E-03	A					4.76E+05	A	8.71E+06	A
Fluoranthene	206-44-0	HPP	2.06E-01	A	5.00E-06	A	6.46E-06	A	3.80E+04	A	7.94E+04	A
Fluorene [2,3-Benzidene]	86-73-7	HPP	1.69E+00	A	7.10E-04	A	6.42E-05	A	7.30E+03	A	1.58E+04	A
Indene	95-13-6										8.32E+02	M
Indeno(1,2,3-cd)pyrene	193-99-5	HPP	5.30E-04	A	1.00E-10	A	6.86E-08	A	1.60E+06	A	3.16E+06	A
2-Methylnapthalene	91-57-6	HSL	2.54E+01	E					8.50E+03	E	1.30E+04	E
Napthalene [Napthene]	91-20-3	HPP	3.17E+01	G	2.30E-01	G	1.15E-03	G	1.30E+03	C	2.76E+03	C
1-Napthylamine	134-32-7		2.35E+03	A	6.50E-05	A	5.21E-09	A	6.10E+01	B	1.17E+02	A
2-Napthylamine	91-59-8		5.86E+02	A	2.56E-04	A	8.23E-08	A	1.30E+02	B	1.17E+02	A
Phenanthrene	85-01-8	HPP	1.00E+00	A	6.80E-04	A	1.59E-04	A	1.40E+04	A	2.88E+04	A
Pyrene	129-00-0	HPP	1.32E-01	A	2.50E-06	A	5.04E-06	A	3.80E+04	A	7.59E+04	A
Tetracene [Napthacene]	92-24-0		5.00E-04	E					6.50E+05	E	8.00E+05	E
AMINES AND AMIDES												
2-Acetylaminofluorene	53-96-3		6.50E+00	A					1.60E+03	B	1.91E+03	A
Acrylamide [2-Propenamide]	79-06-1		2.05E+06	G	7.00E-03	R	3.19E-10	X				
4-Aminobiphenyl [p-Biphenylamine]	92-67-1		8.42E+02	A	6.00E-05	A	1.59E-08	A	1.07E+02	B	6.03E+02	A
Aniline [Benzenamine]	62-53-3	HSL	3.66E+04	G	3.00E-01	G	1.00E-06	X			7.00E+00	E
Auramine	2465-27-2		2.10E+00	A					2.90E+03	B	1.45E+04	A
Benzidine [p-diaminodiphenyl]	92-87-5	HPP	4.00E+02	A	5.00E-04	A	3.03E-07	A	1.05E+01	A	2.00E+01	A
2,4-Diaminotoluene [Toluenediamine]	95-80-7		4.77E+04	A	3.80E-05	A	1.28E-10	A	1.20E+01	B	2.24E+00	A
3,3'-Dichlorobenzidine	91-94-1	HPP	4.00E+00	A	1.00E-05	A	8.33E-07	A	1.55E+03	A	3.16E+03	A
Diethanolamine	111-42-2		9.54E+05	G							3.72E-02	M
Diethylaniline [Benzenamine]	91-66-7		6.70E+02	E							9.00E+00	E
Diethylnitrosamine [Nitrosodiethylamine]	55-18-5				5.00E+00	A					3.02E+00	A
Dimethylamine	124-40-3		1.00E+06	A	1.52E+03	A	9.02E-05	A	4.35E+02	F	4.17E-01	A
Dimethylaminoazobenzene	60-11-7		1.36E+01	A	3.30E-07	A	7.19E-09	A	1.00E+03	B	5.25E+03	A
Dimethylnitrosamine	62-75-9	HPP	infinite	A	8.10E+00	A	7.90E-07	A	1.00E-01	A	2.09E-01	A
Diphenylnitrosamine	86-30-6	HPP									3.72E+02	I
Dipropylnitrosamine	621-64-7	PP	9.90E+03	A	4.00E-01	A	6.92E-06	A	1.50E+01	A	3.16E+01	A

Notes: PP = Priority Pollutant; HSL = Hazardous Substance List Parameter; HPP = PP and HSL Parameters.
Additional notes and data references are provided at end of this table.

Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
Methylvinylnitrosamine	4549-40-0		7.60E+05	A	1.23E+01	A	1.83E-06	A	2.50E+00	B	5.89E-01	A
m-Nitroaniline [3-Nitroaniline]	99-09-2	HSL	8.90E+02	G							2.34E+01	M
o-Nitroaniline [2-Nitroaniline]	88-74-4	HSL	1.47E+04	T							6.17E+01	M
p-Nitroaniline [4-Nitroaniline]	100-01-6	HSL	7.30E+02	T							2.45E+01	M
N-Nitrosodi-n-propylamine	621-64-7	HSL										
Thioacetamide [Ethanethioamide]	62-55-5		1.63E+05	J							3.47E-01	A
o-Toluidine Hydrochloride	636-21-5		1.50E+04	A	1.00E-01	A	9.39E-07	A	2.20E+01	B	1.95E+01	A
o-Toluidine [2-Aminotoluene]	119-93-7		7.35E+01	A	<1.0E+00	R			4.10E+02	B	7.58E+02	A
Triethylamine	121-44-8		1.50E+04	G	7.00E+00	G	1.30E+05	G				
ETHERS AND ALCOHOLS												
Allyl Alcohol [Propenol]	107-18-6		5.10E+05	A	2.46E+01	A	3.69E-06	A	3.20E+00	B	6.03E-01	A
Anisole [Methoxybenzene]	100-66-3		1.52E+03	C	2.60E+00	C	2.43E-04	X	2.00E+01	C	1.29E+02	C
Benzyl Alcohol [Benzenemethanol]	100-51-6	HSL	8.00E+02	S	1.10E-01	S	1.95E-05	X			1.26E+01	M
Bis(2-chloroethyl)ether	111-44-4	HPP	1.02E+04	A	7.10E-01	A	1.31E-05	A	1.39E+01	A	3.16E+01	A
Bis(2-chloroisopropyl)ether	108-60-1	HPP	1.70E+03	A	8.50E-01	A	1.13E-04	A	6.10E+01	A	1.26E+02	A
Bis(chloromethyl)ether	542-88-1		2.20E+04	A	3.00E+01	A	2.06E-04	A	1.20E+00	A	2.40E+00	A
4-Bromophenyl Phenyl Ether	101-55-3	HPP			1.50E-03	I					1.91E+04	I
2-Chloroethyl Vinyl Ether	110-75-8	HPP	1.50E+04	H	2.67E+01	H	2.50E-04	Q			1.90E+01	I
Chloromethyl Methyl Ether	107-30-2										1.00E+00	A
4-Chlorophenyl Phenyl Ether	7005-72-3	HPP	3.30E+00	H	2.70E-03	I	2.19E-04	X			1.20E+04	H
Diphenylether [Phenyl Ether]	101-84-8		2.10E+01	R	2.13E-02	S	8.67E-09	X			1.62E+04	M
Ethanol	64-17-5		infinite	A	7.40E+02	A	4.48E-05	A	2.20E+00	B	4.79E-01	A
PHTHALATES												
Bis(2-ethylhexyl)phthalate	117-81-7	HPP	2.85E-01	C	2.00E-07	C	3.61E-07	X	5.90E+03	D	9.50E+03	C
Butylbenzyl Phthalate	85-68-7	HPP	4.22E+01	G							6.31E+04	H
Di-n-octyl Phthalate	117-84-0	HPP	3.00E+00	H							1.58E+09	I
Dibutyl Phthalate	84-74-2	HPP	1.30E+01	A	1.00E-05	A	2.82E-07	A	1.70E+05	A	3.98E+05	A
Diethyl Phthalate	84-66-2	HPP	8.96E+02	A	3.50E-03	A	1.14E-06	A	1.42E+02	A	3.16E+02	A
Dimethylphthalate	131-11-3	HPP	4.32E+03	H	<1.0E-02	H					1.32E+02	I
KETONES AND ALDEHYDES												
2-Butanone [Methyl Ethyl Ketone]	78-93-3	HSL	2.68E+05	A	7.75E+01	A	2.74E-05	A	4.50E+00	B	1.82E+00	A
2-Hexanone [Methyl Butyl Ketone]	591-78-6	HSL	1.40E+04	R	3.00E+10	R	2.82E-05	R				
4-Methyl-2-Pentanone [Isopropylacetone]	108-10-1	HSL	1.70E+04	S	2.00E+01	R	1.55E-04	X				
Acetone [2-Propanone]	67-64-1	HSL	infinite	A	2.70E+02	A	2.06E-05	A	2.20E+00	B	5.75E-01	A
Formaldehyde	50-00-0		4.00E+05	A	1.00E+01	A	9.87E-07	A	3.60E+00	B	1.00E+00	A
Glycidaldehyde	765-34-4		1.70E+08	A	1.97E+01	A	1.10E-08	A	1.00E-01	B	2.82E-02	A
Acrylic Acid [2-Propenoic Acid]	79-10-7		infinite	A	4.00E+00	A					1.35E+00	A

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Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
CARBOXYLIC ACIDS AND ESTERS												
Azaserine	115-02-6		1.36E+05	A					6.60E+00	B	8.32E-02	A
Benzoic Acid	65-85-0	HSL	2.70E+03	G							7.41E+01	H
Dimethyl Sulfate [DMS]	77-78-1		3.24E+05	A	6.80E-01	A	3.48E-07	A	4.10E+00	B	5.75E-02	A
Ethyl Methanesulfonate [EMS]	62-50-0		3.69E+05	A	2.06E-01	A	9.12E-08	A	3.80E+00	B	1.62E+00	A
Formic Acid	64-18-6		1.00E+06	A	4.00E+01	A					2.88E-01	A
Lasiocarpine	303-34-4		1.60E+03	A					7.60E+01	B	9.77E+00	A
Methyl Methacrylate	80-62-6		2.00E+01	A	3.70E+01	A	2.43E-01	A	8.40E+02	B	6.17E+00	A
Vinyl Acetate	108-05-4	HSL	2.00E+04	J								
PCBs												
Aroclor 1016	12674-11-2	HPP	4.20E-01	H	4.00E-04	I					2.40E+04	H
Aroclor 1221	11104-28-2	HPP	1.50E+01	I	6.70E-03	I					1.23E+04	H
Aroclor 1232	11141-16-5	HPP	1.45E+00	I	4.06E-03	I					1.58E+03	I
Aroclor 1242	53469-21-9	HPP	2.40E-01	G	4.10E-04	G	5.60E-04	G			1.29E+04	I
Aroclor 1248	12672-29-6	HPP	5.40E-02	G	4.90E-04	G	3.50E-03	G			5.62E+05	I
Aroclor 1254	11097-69-1	HPP	1.20E-02	G	7.70E-05	G	2.70E-03	G	4.25E+04	E	1.07E+06	I
Aroclor 1260	11096-82-5	HPP	2.70E-03	G	4.10E-05	G	7.10E-03	G			1.38E+07	I
Polychlorinated Biphenyls [PCBs]	1336-36-3	HPP	3.10E-02	A	7.70E-05	A	1.07E-03	A	5.30E+05	A	1.10E+06	A
HETEROCYCLIC COMPOUNDS												
Dihydrosafrole	94-58-6		1.50E+03	A					7.80E+01	B	3.63E+02	A
1,4-Dioxane [1,4-Diethylene Dioxide]	123-91-1		4.31E+05	A	3.99E+01	A	1.07E-05	A	3.50E+00	B	1.02E+00	A
Epichlorohydrin	106-89-8		6.00E+04	A	1.57E+01	A	3.19E-05	A	1.00E+01	B	1.41E+00	A
Isosafrole	120-58-1		1.09E+03	A	1.60E-08	A	3.25E-12	A	9.30E+01	B	4.57E+02	A
N-Nitrosopiperidine	100-75-4		1.90E+06	A	1.40E-01	A	1.11E-08	A	1.50E+00	B	3.24E-01	A
N-Nitrosopyrrolidine	930-55-2		7.00E+06	A	1.10E-01	A	2.07E-09	A	8.00E-01	B	8.71E-02	A
Safrole	94-59-7		1.50E+03	A	9.10E-04	A	1.29E-07	A	7.80E+01	B	3.39E+02	A
Uracil Mustard	66-75-1		6.41E+02	A					1.20E+02	B	8.13E-02	A
HYDRAZINES												
1,2-Diethylhydrazine	1615-80-1		2.88E+07	A					3.00E-01	B	2.09E-02	A
1,1-Dimethylhydrazine	57-14-4		1.24E+08	A	1.57E+02	A	1.00E-07	A	2.00E-01	B	3.80E-03	A
1,2-Diphenylhydrazine [Hydrazobenzene]	122-66-7	PP	1.84E+03	A	2.60E-05	A	3.42E-09	A	4.18E+02	A	7.94E+02	A
Hydrazine	302-01-1		3.41E+08	A	1.40E+01	A	1.73E-09	A	1.00E-01	B	8.32E-04	A
MISCELLANEOUS ORGANIC COMPOUNDS												
Aziridine [Ethylenimine]	151-56-4		2.66E+06	A	2.55E+02	A	5.43E-06	A	1.30E+00	B	9.77E-02	A
Carbon Disulfide	75-15-0	HSL	2.94E+03	A	3.60E+02	A	1.23E-02	A	5.40E+01	B	1.00E+02	A

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Table A-1. Water Solubility, Vapor Pressure, Henry's Law Constant, Koc, and Kow Data for Selected Chemicals.

Chemical Name	CAS #	EPA	Water Solubility (mg/l)	Ref	Vapor Pressure (mm Hg)	Ref	Henry's Law Constant (atm-m3/mol)	Ref	Koc (ml/g)	Ref	Kow	Ref
Diethyl Arsine	692-42-2		4.17E+02	A	3.50E+01	A	1.48E-02	A	1.60E+02	B	9.33E+02	A
Dimethylcarbamoyl Chloride	79-44-7		1.44E+07	A	1.95E+00	A	1.92E-08	A	5.00E-01	B	4.79E-02	A
Mercury and Compounds (Alkyl)	7439-97-6	PP							1.00E-01	B	1.54E-04	A
Methylnitrosourea	684-93-5		6.89E+08	A					1.10E+02	B	2.34E+01	A
Mustard Gas [bis(2-chloroethyl)sulfide]	505-60-2		8.00E+02	A	1.70E-01	A	4.45E-05	A	9.80E+01	B	6.46E-01	A
Phenobarbital	50-06-6		1.00E+03	A					2.30E+00	B	3.31E-01	A
Propylenimine	75-55-8		9.44E+05	A	1.41E+02	A	1.12E-05	A	4.90E+03	B		
Tetraethyl Lead	78-00-2		8.00E-01	A	1.50E-01	A	7.97E-02	A	1.60E+00	B	8.91E-03	A
Thiourea [Thiocarbamide]	62-56-6		1.72E+06	A					3.10E+02	B	1.32E+04	A
Tris-BP [2,3-Dibromolpropanol phosphate]	126-72-7		1.20E+02	A								
INORGANICS												
Ammonia	7664-41-7		5.30E+05	A	7.60E+03	A	3.21E-04	A	3.10E+00	B	1.00E+00	A
Antimony and Compounds	7440-36-0	PP			1.00E+00	A						
Arsenic and Compounds	7440-38-2	PP			0.00E+00	A						
Barium and Compounds	7440-39-3											
Beryllium and Compounds	7440-41-7	PP			0.00E+00	A						
Cadmium and Compounds	7740-43-9	PP			0.00E+00	A						
Chromium III and Compounds	7440-47-3	PP			0.00E+00	A						
Chromium VI and Compounds	7440-47-3	PP			0.00E+00	A						
Copper and Compounds	7440-50-8	PP			0.00E+00	A						
Cyanogen Chloride	506-77-4		2.50E+03	A	1.00E+03	A	3.24E-02	X			1.00E+00	A
Hydrogen Cyanide	74-90-8		infinite	A	6.20E+02	A					5.62E-01	A
Hydrogen Sulfide	7783-06-4		4.13E+03	A	1.52E+04	R	1.65E-01	R				
Lead and Compounds	7439-92-1	PP			0.00E+00	A						
Mercury and Compounds (Inorganic)	7439-97-6	PP	3.00E-02	G	2.00E-03	A	1.10E-02	G				
Nickel and Compounds	7440-02-0	PP			0.00E+00	A						
Potassium Cyanide	151-50-8		5.00E+05	A								
Selenium and Compounds	7782-49-2	PP			0.00E+00	A						
Silver and Compounds	7440-22-4	PP			0.00E+00	A						
Sodium Cyanide	143-33-9		8.20E+05	A								
Thallium Chloride	7791-12-0	PP	2.90E+03	A	0.00E+00	A						
Thallium Sulfate	7446-18-6	PP	2.00E+02	A	0.00E+00	A						
Thallium and Compounds	7440-28-0	PP			0.00E+00	A						
Zinc and Compounds	7440-66-6	PP			0.00E+00	A						

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Table A-2. Specific Gravity and Viscosity Data for Selected Petroleum Products.

Petroleum Product	Specific Gravity @15-25 deg.C.	Refs	Kinematic Viscosity Values in Centistokes @ 10 deg.C.	Ref	@ 20 deg.C.	Ref	@ 40 deg.C.	Ref	@ 100 deg.C.	Ref	Absolute Viscosity Values in Centipoise @ 10 deg.C.	Ref	@ 20 deg.C.	Ref	Value @ deg. C.		Ref
Crude Oil	0.7 - 1.0	A									8 - 87	B			1.6-739.	38	D
Gasoline	0.73-0.76	A,D											0.45	L	0.3	38	C
Kerosene	0.81	D											2.05	E			
Naptha	0.85-0.97	D															
No.1-D Diesel Fuel	0.80-0.82	C					1.3-2.4	F							1.1-1.9	40	*
No.2-D Diesel Fuel	0.85	C					1.9-4.1	F							1.6-3.5	40	*
No.4-D Diesel Fuel							5.5-24.	F									
Marine Diesel Fuel	0.83	B													10.	38	B
Jet A Aviation Fuel	0.77-0.84	F													1.0-1.5	38	C
Jet B Aviation Fuel	0.75-0.80	F															
80 Grade Aviation Gas	0.70	G															
100 Grade Aviation Gas	0.70	G															
100LL Grade Aviation Gas	0.71	G															
Jet Fuel JP-1	0.80	J															
Jet Fuel JP-3	0.80	J															
Jet Fuel JP-4	0.81	J															
Jet Fuel JP-5	0.82	J															
No.1 Gas Turbine Fuel Oil	0.850	F					1.3-2.4	F							1.1-2.0	40	*
No.2 Gas Turbine Fuel Oil	0.876	F					1.9-4.1	F							1.7-3.6	40	*
No.3 Gas Turbine Fuel Oil							>5.5	F									
No.4 Gas Turbine Fuel Oil							>5.5	F									
No.1 Fuel Oil	0.81-0.85	D,F,G					1.4-2.2	F							1.2-1.8	40	*
No.2 Fuel Oil	0.86-0.88	D,F,G					2.0-3.6	F					5.92	E	1.7-3.2	40	*
No.4 (Light) Fuel Oil	0.876	F					2.0-5.8	F							1.7-5.1	40	*
No.4 Fuel Oil	0.87-1.01	D,G					5.5-24.0	F					12.6	E	4.8-24.2	40	*
No.5 (Light) Fuel Oil							>24.0-58	F									
No.5 Fuel Oil	0.92-1.04	D,G					>58-168	F							76.	50	G
No.6 Fuel Oil	0.94-1.05	D,G									28000000	B			60.-150.	38	A
Aero Oil Grade 100			1400.	I	650.	I	193.	G	20.2	G							
Aero Oil Grade 120			2500.	I	1100.	I	296.	G	23.4	G							
Aero Oil Grade 20W-50			3000.	I	1200.	I	189.	G	19.	G							
Aviation Oil Grade 100			2000.	I	850.	I	224.	G	19.1	G							
Aviation Oil Grade 120			3200.	I	1400.	I	329.	G	24.	G							
SAE 10W Motor Oil	0.877	K	205.	I	110.	I	41-43	G	7.	G	179.	*	52.3	E			
SAE 30 Motor Oil	0.887	K	950.	I	420.	I	107-134	G	11-13	G	840.	*	352.	E			
SAE 40 Motor Oil	0.892	K	1500.	I	650.	I	147-188	G	15.	G	1310.	*	570.	*			
SAE 50 Motor Oil	0.897	K	2500.	I	1000.	I	234-250	G	19.	G	2240.	*	880.	E			
SAE 5W-30 Motor Oil			220.	I	145.	I	59.	G	11.9	G							
SAE 10W-30 Motor Oil	0.869	K	220.	I	145.	I	64.	G	11.7	G	190.	*	130.	*			
SAE 10W-40 Motor Oil	0.870	K	430.	I	245.	I	95.	G	15.9	G	370.	*	210.	*			
SAE 15W-40 Motor Oil	0.880	K	800.	I	400.	I	120.	G	15.0	G	700.	*	350.	*			
SAE 15W-50 Motor Oil	0.874	K	650.	I	350.	I	121.	G	18.0	G	570.	*	310.	*			
SAE 20W-20 Motor Oil	0.883	K	500.	I	240.	I	73.	G	9.0	G	440.	*	210.	*			
Auto Transmission Fluid	0.895	G	150.	I	87.	I	35-36	G	5.9-7.1	G	130.	*	80.	*			
Tractor Hydraulic Fluid	0.894	G	310.	I	160.	I	54.	G	7.7	G	280.	*	140.	*			

Table A-2. Specific Gravity and Viscosity Data for Selected Petroleum Products.

Petroleum Product	Specific Gravity @15-25 deg.C.	Refs	Kinematic Viscosity Values in Centistokes @ 10 deg.C.	Ref	@ 20 deg.C.	Ref	@ 40 deg.C.	Ref	@ 100 deg.C.	Ref	Absolute Viscosity Values in Centipoise @ 10 deg.C.	Ref	@ 20 deg.C.	Ref	Value @ deg. C.	Ref
Aviation Hydraulic Fluid Grades A & E	0.873	G					13.5	G								
AW Hydraulic Oil Grade 32	0.863	G	150.	I	80.	I	31.5	G	5.5	G	129.	*	69.	*		
AW Hydraulic Oil Grade 46	0.867	G	250.	I	130.	I	44.0	G	6.6	G	217.	*	113.	*		
AW Hydraulic Oil Grade 68	0.870	G	390.	I	200.	I	65.0	G	8.8	G	339.	*	174.	*		
AW Hydraulic Oil Gr. 100	0.885	G	650.	I	310.	I	96.0	G	11.0	G	575.	*	274.	*		
AW Hydraulic Oil Gr. 150	0.886	G	1000.	I	470.	I	138.2	G	14.1	G	886.	*	416.	*		
AW Hydraulic Oil Grade HV	0.884	G	125.	I	70.	I	30.0	G	5.9	G	110.	*	62.	*		
Aw Machine Oil Grade 10	0.871	G	32.	I	20.	I	9.6	G	2.5	G	28.	*	17.	*		
AW Machine Oil Grade 22	0.877	G	90.	I	50.	I	21.	G	4.1	G	79.	*	44.	*		
AW Machine Oil Grade 32	0.877	G	150.	I	80.	I	30.	G	5.2	G	132.	*	70.	*		
AW Machine Oil Grade 46	0.878	G	250.	I	130.	I	43.	G	6.5	G	220.	*	114.	*		
AW Machine Oil Grade 68	0.878	G	390.	I	200.	I	64.	G	8.4	G	342.	*	176.	*		
AW Machine Oil Grade 100	0.881	G	650.	I	310.	I	94.	G	10.8	G	573.	*	273.	*		
AW Machine Oil Grade 150	0.883	G	1000.	I	470.	I	140.	G	14.	G	883.	*	415.	*		
AW Machine Oil Grade 220	0.888	G	1850.	I	800.	I	210.	G	18.3	G	1640.	*	710.	*		
AW Machine Oil Grade 320	0.894	G	3000.	I	1300.	I	305.	G	23.4	G	2680.	*	1160.	*		
Cylinder Oil Grade 460X	0.910	G	5200.	I	2000.	I	440.	G	26.4	G	4730.	*	1790.	*		
Cylinder Oil Grade 680X	0.922	G	9500.	I	3200.	I	650.	G	33.2	G	8760.	*	2950.	*		
Cylinder Oil Grade 1000X	0.922	G	17000.	I	5500.	I	950.	G	39.4	G	15700.	*	5070.	*		
Edger Arbor Oil X	0.906	G	215.	I	108.	I	36.	G	5.3	G	195.	*	98.	*		
EP Industrial Oil Gr. 46X	0.872	G	250.	I	130.	I	44.	G	6.5	G	218.	*	113.	*		
EP Industrial Oil Gr.100X	0.878	G	650.	I	310.	I	95.	G	10.7	G	571.	*	272.	*		
EP Industrial Oil Gr.150X	0.883	G	1000.	I	470.	I	140.	G	13.9	G	883.	*	415.	*		
EP Industrial Oil Gr.220X	0.889	G	1850.	I	800.	I	210.	G	18.2	G	1640.	*	711.	*		
EP Industrial Oil Gr.320X	0.903	G	3000.	I	1300.	I	304.	G	23.2	G	2710.	*	1170.	*		
EP Industrial Oil Gr.460X	0.900	G	5200.	I	2000.	I	440.	G	28.5	G	4680.	*	1800.	*		
Lubricating Oil Grade 32X	0.871	G	150.	I	80.	I	29.	G	5.2	G	131.	*	70.	*		
Lubricating Oil Gr. 100X	0.887	G	650.	I	310.	I	92.	G	10.7	G	577.	*	275.	*		
Lubricating Oil Gr. 105X	0.884	G	700.	I	330.	I	90.	G	10.5	G	619.	*	292.	*		
Lubricating Oil Gr. 460X	0.892	G	5200.	I	2000.	I	440.	G	29.5	G	4640.	*	1780.	*		
Turbine Oil Grade 32	0.864	G	150.	I	80.	I	31.	G	5.4	G	130.	*	69.	*		
Turbine Oil Grade 46	0.875	G	250.	I	130.	I	44.	G	6.6	G	219.	*	114.	*		
Turbine Oil Grade 68	0.877	G	390.	I	200.	I	65.	G	8.5	G	342.	*	175.	*		
Turbine Oil Grade 100	0.880	G	650.	I	310.	I	94.	G	10.7	G	572.	*	273.	*		
Heat Transfer Oil Grade 1	0.882	G	230.	I	120.	I	42.	G	6.6	G	203.	*	106.	*		
Heat Transfer Oil Gr. 20	0.857	G	85.	I	48.	I	20.0	G	4.04	G	73.	*	41.	*		
Marine Oil Grade 150X	0.928	G	2000.	I	790.	I	168.	G	12.7	G	1860.	*	733.	*		
Marine Oil Grade 220X	0.934	G	2400.	I	960.	I	220.	G	17.	G	2240.	*	205.	*		
Cutting Oil MW Fluid 11A			200.	I	108.	I	40.	G	6.6	G						
Cutting Oil MW Fluid 11D	0.829	K					4.23	G							3.51	40 *
Cutting Oil MW Fluid 21D	0.921	K	180.	I	92.	I	31.	G	4.7	G	166.	*	85.	*		
Cutting Oil MW Fluid 31A	0.891	K	92.	I	52.	I	21.	G	4.3	G	82.	*	46.	*		
Cutting Oil MW Fluid 31B			97.	I	52.	I	20	G.	3.7	G						
Cutting Oil MW Fluid 31C	0.916	K	200.	I	105.	I	35.	G	5.3	G	183.	*	96.	*		

Table A-2. Specific Gravity and Viscosity Data for Selected Petroleum Products.

Petroleum Product	Specific Gravity @15-25 deg.C.	Refs	Kinematic Viscosity Values in Centistokes @ 10 deg.C.	Ref	@ 20 deg.C.	Ref	@ 40 deg.C.	Ref	@ 100 deg.C.	Ref	Absolute Viscosity Values in Centipoise @ 10 deg.C.	Ref	@ 20 deg.C.	Ref	Value @ deg. C.	Ref
Cutting Oil MW Fluid 41B	0.907	K	120.	I	65.	I	23.	G	3.9	G	109.	*	59.	*		
Cutting Oil MW Fluid 41D	0.914	K	170.	I	85.	I	30.	G	4.8	G	155.	*	78.	*		
Cutting Oil MW Fluid 41E	0.897	K	145.	I	80.	I	31.	G	5.5	G	130.	*	72.	*		
Cutting Oil MW Fluid 41M	0.898	K	77.	I	45.	I	19.	G	3.9	G	69.	*	40.	*		
Cutting Oil MW Fluid 43B	0.908	K	170.	I	85.	I	30.	G	4.8	G	154.	*	77.	*		
Cutting Oil MW Fluid 44A	0.894	K	155.	I	82.	I	29.	G	4.8	G	139.	*	73.	*		
Cutting Oil MW Fluid 45A	0.925	K	210.	I	110.	I	38.	G	6.0	G	194.	*	102.	*		
Cutting Oil MW Fluid 45B	0.936	K	500.	I	230.	I	67.	G	7.8	G	468.	*	215.	*		
Refrigeration Oil Gr. 32	0.894	G	190.	I	90.	I	30.	G	4.3	G	170.	*	80.	*		
Refrigeration Oil Gr. 68	0.910	G	500.	I	230.	I	65.	G	7.3	G	455.	*	209.	*		
RPM Chain Bar Oil Gr. 150			1250.	D	525.	D	139.	G	12.8	G						
RPM Chain Bar Oil Gr. 220			1800.	D	800.	D	212.	G	19.	G						
SAE 75W-90 Artic Gear Oil			480.	D	230.	D	91.	G	14.6	G						
SAE Grade 90 Gear Oil	0.888	G	1800.	I	800.	I	213.	G	18.8	G	1600.	*	710.	*		
SAE Grade 140 Gear Oil	0.902	G	4900.	I	1900.	I	452.	G	30.3	G	6420.	*	1710.	*		
ML Gear Lubricant Gr. 68	0.874	G	300.	I	170.	I	63.	G	10.0	G	262.	*	149.	*		
ML Gear Lubricant Gr. 100	0.876	G	650.	I	310.	I	93.	G	11.0	G	569.	*	272.	*		
ML Gear Lubricant Gr. 150	0.896	G	960.	I	450.	I	142.	G	14.3	G	860.	*	403.	*		
ML Gear Lubricant Gr. 220	0.888	G	1800.	I	800.	I	201.	G	17.8	G	1600.	*	710.	*		
ML Gear Lubricant Gr. 320	0.893	G	3000.	I	1300.	I	304.	G	22.0	G	2680.	*	1160.	*		
ML Gear Lubricant Gr. 460	0.989	G	5000.	I	1900.	I	435.	G	27.5	G	4490.	*	1710.	*		
ML Gear Lubricant Gr. 680			9500.	D	3300.	D	640.	G	33.5	G						
ML Gear Lubricant Gr.1000			12000.	D	4500.	D	935.	G	53.2	G						
ML Gear Lubricant Gr.1500			22000.	D	7500.	D	1400.	G	98.8	G						
ML Gear Lubricant Gr.2200							2150.	G								

References and Notes:

A = CONCAWE, 4/79, Protection of Groundwater from Oil Pollution.
B = Payne, J.R., and C.R. Phillips, 1985, Petroleum Spills in the Marine Environment, Lewis Publishers, Chelsea, MI.
C = National Institute for Petroleum and Energy Research, 1988, Personal communication.
D = Breuel, A., 1981, Oil Spill Cleanup and Protection Techniques for Shorelines and Marshlands, Noyes Data, N.J.
E = Cole-Parmer Co., 1989-1990, Equipment Catalog.
F = ASTM, 1985, Annual Book of ASTM Standards, Section 5, Petroleum Products, Lubricants, and Fossil Fuels, Philadelphia.
G = Chevron USA, Inc., 1988, Product Salesfax Digest, San Francisco.
H = Weast, R.C., (ed.), 1980-1981, CRC Handbook of Chemistry and Physics, 61st Edition, Cleveland.
I = Values calculated using ASTM viscosity-temperature charts for liquid petroleum products (ASTM D 341-77).
J = U.S. Coast Guard, 1979, CHRIS Hazardous Chemical Data.
K = Chevron USA, Inc., 1989, Personal Communication.
L = Hunt, J.R., N. Sitar, and K.S. Udell, 1988, Nonaqueous Phase Liquid Transport and Cleanup 1. Analysis of Mechanisms, in Water Resources Research, Vol.24, No.8, pp.1247-1258.
* = Values calculated based on: Absolute Viscosity (centipoise) = Kinematic Viscosity (centistokes) X Specific Gravity.

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
Acetaldehyde	0.7780	20	A	0.244	20	A
Acetic Acid	1.0492	20	A	1.314	15	A
Acetic Anhydride	1.0811	20	A	0.971	15	A
Acetone [2-Propenone]	0.7908	20	A	0.337	15	A
Acetonitrile [Methyl Cyanide]	0.7822	20	A	0.375	20	A
Acetophenone	1.0238	25	A	1.642	25	A
Acetyl Bromide	1.663	16	A			
Acetyl Chloride	1.105	20	A			
Acrolein [2-Propenal]	0.8389	20	A			
Acrylic Acid [2-Propenoic Acid]	1.0511	20	A			
Acrylonitrile [2-Propenenitrile]	0.8060	20	A	0.35	20	A
Adiponitrile	0.950	20	A			
Allyl Acetate	0.9256	20	A	0.207	30	A
Allylamine	0.7629	20	A	0.375	25	A
2-Aminoethanol	1.0116	25	A	19.35	25	A
1-Amino-2-methylpropane	0.7297	25	A	21.7	25	A
Aniline	1.0217	20	A	4.400	20	A
Benzaldehyde	1.0447	20	A	1.321	25	A
Benzene	1.8737	25	A	0.6028	25	A
Benzenethiol	1.0766	20	A	1.239	20	A
Benzonitrile	1.0051	20	A	1.447	15	A
Benzophenone				4.79	55	B
Benzoyl Chloride	1.211	20	A			
Benzyl Acetate	1.055	20	A	1.399	45	A
Benzyl Alcohol	1.045	20	A	7.760	15	A
Benzylamine	0.9813	20	B	1.59	25	B
Benzylaniline				2.18	33	B
Benzyl Benzoate	1.1121	25	A	8.292	25	A
Benzyl Ether				5.33	20	B
Benzyl Ethyl Ether	0.9478	20	A			
Bicyclohexane	0.8862	20	A	3.75	20	A
Bis(2-chloroethyl)ether	1.2130	25	A	2.14	25	A
Bis(2-ethylhexyl)phthalate	0.9843	20	A	81.4	20	A
Bis(2-methoxyethyl)ether	0.9440	25	A	0.981	25	A
Bromine				0.995	19	B
2-Bromoaniline [o-Bromoaniline]	1.578	20	B	3.19	40	B
3-Bromoaniline [m-Bromoaniline]	1.579	20	A	6.81	20	B
4-Bromoaniline [p-Bromoaniline]	1.4970	99	B	1.61	80	B
Bromobenzene	1.4882	25	A	0.985	30	A
1-Bromobutane	1.2758	20	A	0.633	20	A
2-Bromobutane	1.255	20	A			
Bromodichloromethane	1.97	20	D	1.71	20	D
Bromoethane	1.4708	15	A	0.418	15	A
Bromoethene	1.517	20	A			
1-Bromohexane	1.176	20	A			
1-Bromonapthalene	1.4834	20	A	5.99	15	A
1-Bromopropane	1.3597	15	A	0.539	15	A
2-Bromopropane	1.3222	15	A	0.536	15	A
o-Bromotoluene	1.422	20	A			
1-Butanal	0.8016	20	A	0.455	20	A
2-Butanal	0.7891	20	A			
1-Butanamine	0.7392	20	A	0.681	20	A
2-Butanamine	0.7246	20	A			
1,3-Butanediol	1.0053	20	A	130.3	20	A
Butanenitrile	0.7954	15	A	0.624	20	A
1-Butanethiol	0.8416	20	A	0.501	20	A
Butanoic Acid	0.9582	20	A	1.814	15	A
1-Butanol	0.8097	20	A	3.379	15	A
2-Butanol	0.8069	20	A	4.210	20	A
2-Butanone [Methyl Ethyl Ketone]	0.8047	20	A	0.423	15	A
cis-2-Butene-1,4-diol	1.0740	20	A			
trans-2-Butene-1,4-diol	1.0685	20	A			
2-Butnxyethanol	0.8964	25	A	3.15	25	A

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
Butyl Acetate	0.8813	20	A	0.734	20	A
Butylbenzene	0.8601	20	A	1.035	20	A
sec-Butylbenzene	0.8621	20	A	28.53	20	A
tert-Butylbenzene	0.8665	20	A	28.13	20	A
Butyl Ethyl Ether	0.7495	20	A	0.421	20	A
Butyl Formate	0.8917	20	A	0.704	20	A
Butyl Octyl Phthalate	0.992	20	C	42.	25	C
Butyl Oleate	0.864	20	A			
Butyl Stearate	0.8540	25	A	8.26	25	A
Butyric Anhydride	0.9668	20	A	1.615	20	A
y-Butylactone	1.1254	25	A	1.7	25	A
D-Camphor	0.9920	20	A			
Carbon Disulfide	1.2628	20	A	0.363	78	A
o-Chloroaniline	1.2077	25	A	0.925	25	A
Chlorobenzene	1.1063	20	A	0.799	20	A
1-Chlorobutane	0.8864	20	A	0.469	15	A
2-Chlorobutane	0.8732	20	A	0.439	15	A
1-Chloro-2,3-epoxypropane	1.1746	25	A	1.03	25	A
Chlcroethane	0.0903	15	A	0.279	10	A
2-Chloroethanol	1.2072	15	A	3.913	15	A
Chloromethane [Methyl Chloride]	0.9159	20	B	0.449	15	B
1-Chloro-2-methylpropane	0.8829	15	A	0.471	15	A
2-Chloro-2-methylpropane	0.8414	20	A	0.543	15	A
1-Chloronapthalene	1.1930	25	A	2.940	25	A
1-Chloropentane	0.8840	20	A	0.580	20	A
o-Chlorophenol [2-Chlorophenol]	1.2410	18	A	2.250	45	A
m-Chlorophenol [3-Chlorophenol]	1.268	25	B	11.55	25	B
p-Chlorophenol [4-Chlorophenol]	1.2651	40	A	6.018	45	A
1-Chloropropane	0.8923	20	A	0.372	15	A
2-Chloropropane	0.8617	20	A	0.335	15	A
3-Chloro-1-propene	0.9376	20	A	0.347	15	A
Chlorotoluene (Benzyl Chloride)	1.0993	20	A	1.400	20	A
o-Chlorotoluene	1.0817	20	A			
p-Chlorotoluene	1.0697	20	A			
1,8-Cineole	0.9192	25	A			
Cinnamaldehyde	1.0497	20	A			
o-Cresol				4.49	40	B
m-Cresol	1.0380	15	A	24.67	15	A
p-Cresol	1.0140	46	A	5.607	46	A
Crotonaldehyde (2-Butenal)	0.8516	20	A			
Cyclohexanamine	0.8671	20	A	1.662	20	A
Cyclohexane	0.7786	20	A	0.980	20	A
Cyclohexanol	0.9416	30	A	41.07	30	A
Cyclohexanone	0.9462	20	A	2.453	15	A
Cyclohexene	0.8110	20	A	0.650	20	A
Cyclohexylbenzene	0.9427	20	A	3.681	0	A
Cyclopentane	0.7454	20	A	0.439	20	A
p-Cymene	0.8573	20	A	3.402	20	A
cis-Decahydronapthalene	0.8967	20	A	3.381	20	A
trans-Decahydronapthalene	0.8697	20	A	2.128	20	A
Decane	0.7301	20	A	0.928	20	A
1-Decanol	0.8297	20	A			
1-Decene	0.7408	20	A	0.805	20	A
Diallyl Phthalate	1.117	25	C	9.	25	C
Dibenzylamine	1.0278	20	A			
Dibenzyl Ether	0.9974	25	A	3.711	35	A
1,2-Dibromoethane [EDB]	2.1687	25	A	1.490	30	A
cis-Dibromoethene	2.2464	20	A			
trans-1,2-Dibromoethene	2.2308	20	A			
Dibromomethane	2.4921	20	A			
1,2-Dibromotetrafluoroethane	2.163	25	A	0.72	25	A
Dibutylamine	0.7619	20	A	0.95	20	A
Dibutyl Ether	0.7646	25	A	0.602	30	A

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
Dibutyl Maleate	0.9950	20	A	5.63	20	A
Dibutyl Phthalate	1.0426	25	A	16.47	25	A
Dibutyl Sebacate	0.9324	25	A	7.96	25	A
1,2-Dichlorobenzene	1.3003	25	A	1.324	25	A
1,3-Dichlorobenzene	1.2828	25	A	1.04	25	A
1,4-Dichlorobenzene	1.2417	60	A	0.720	70	A
1,1-Dichloroethane	1.1835	15	A	0.505	25	A
1,2-Dichloroethane	1.2600	15	A	0.887	15	A
1,1-Dichloroethene	1.22	20	D	0.36	20	D
1,2-Dichloroethene (trans)	1.2546	20	A	0.404	20	A
1,2-Dichloroethene (cis)	1.2736	25	A	0.444	25	A
Dichloromethane (Methylene Cl-)	1.3348	15	A	0.449	15	A
1,2-Dichloropropane	1.558	20	A			
1,3-Dichloropropane	1.1859	20	A			
2,3-Dichloropropane	1.0912	20	A	0.769	15	A
Diethanolamine	1.0899	30	A	380.	30	A
Di(2-ethylhexyl) Adipate	0.927	20	C	13.5	20	C
1,1-Diethyoxyethane	0.8254	20	A			
Diethylamine	0.7056	20	A	0.388	10	A
Diethylaniline	0.9351	29	B	2.18	20	B
Diethyl Carbonate	0.9804	15	A	0.868	15	A
Diethyl Ether	0.7193	15	A	0.247	15	A
Di(2-ethylhexyl) Phthalate	0.986	20	C	80.	20	C
Diethyl Maleate	1.0637	25	A	3.14	25	A
Diethyl Malonate	1.0550	20	A	2.15	20	A
Diethyl Oxalate	1.0843	15	A	2.311	15	A
Diethyl Phthalate	1.120	20	C	9.5	20	C
Diethyl Sulfate	1.1774	20	A			
Diethyl Sulfide	0.8367	20	A	0.446	20	A
Diiodomethane	3.3078	25	A	2.392	30	A
Diisoamyl Ether	0.7777	20	A	1.40	11	A
Diisodecyl Phthalate	0.966	20	C	108.	20	C
Diisononyl Phthalate	0.969	25	C	72.	25	C
Diisopropylamine	0.7153	20	A	0.40	25	A
Diisopropyl Ether	0.7325	25	A	0.379	25	A
1,2-Dimethoxybenzene	1.0819	25	A	3.281	25	A
1,2-Dimethoxyethane	0.8621	25	A	0.455	25	A
Di(methoxyethyl) Phthalate	1.171	20	C	53.	20	C
Dimethoxymethane	0.8665	15	A	0.340	15	A
N,N-Dimethylacetamide	0.9366	25	A	0.838	30	A
Dimethylamine	1.6616	15	A	0.207	15	A
N,N-Dimethylaniline	0.9559	20	A	1.285	25	A
2,2-Dimethylbutane	0.6445	25	A	0.351	25	A
2,3-Dimethylbutane	0.6570	25	A	0.361	25	A
2,2-Dimethyl-1-butanol	0.8286	20	A			
2,3-Dimethyl-1-butanol	0.8300	20	A			
3,3-Dimethyl-2-butanol	0.8179	20	A			
N,N-Dimethylformamide	0.9445	20	A	0.802	20	A
Dimethyl Maleate	1.1513	20	A	3.54	20	A
2,3-Dimethylpentane	0.6951	20	A	0.406	20	A
2,4-Dimethylpentane	0.6727	20	A	0.361	20	A
Dimethylphthalate	1.1905	21	A	11.	20	C
2,2-Dimethylpropane	0.5910	20	A	0.303	5	A
Dimethyl Sulfate	1.3322	20	A			
Dimethyl Sulfoxide	1.0958	25	A	1.996	25	A
Dioctyl Terephthalate	0.984	20	C	63	25	C
1,4-Dioxane	1.0280	25	A	1.439	15	A
Dipentyl Ether	0.7790	25	A	0.922	30	A
Diphenyl Ether	1.0661	30	A	1.158	30	A
Diphenylmethane	1.0060	20	A			
Dipropylamine	0.7375	20	A	0.534	20	A
Dipropyl Ether	0.7518	15	A	0.448	15	A
Dodecane	0.7487	20	A	1.508	20	A

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
1-Dodecanol	0.8343	20	A			
1,2-Epoxybutane	0.8297	20	A	0.41	20	A
1,2-Ethanediamine	0.8977	20	A	1.54	25	A
1,2-Ethanediol	1.1171	15	A	26.09	15	A
1,2-Ethanediol Diacetate	1.1043	20	A	3.13	20	A
Ethanol	0.7851	25	A	1.078	25	A
Ethoxybenzene	0.9651	20	A	1.364	15	A
2-Ethoxyethanol	0.9295	20	A	2.05	20	A
2-(2-ethoxyethoxy)ethanol	0.9841	25	A	3.71	25	A
2-(2-ethoxyethoxy)ethyl Acetate	1.0096	20	A	2.8	20	A
2-Ethoxyethyl Acetate	0.9730	25	A	1.025	25	A
Ethyl Acetate	0.8946	25	A	0.426	25	A
Ethyl Acetoacetate	1.025	20	A	1.508	20	A
Ethyl Acrylate	0.9234	20	A			
Ethylbenzene	0.8670	20	A	0.678	20	A
Ethyl Benzoate	1.0465	20	A	2.407	15	A
2-Ethyl-1-butanol	0.8330	20	A	5.892	25	A
Ethyl Butyrate	0.8794	20	A	0.672	20	A
Ethyl Cinnamate	1.0494	20	A	8.7	20	A
Ethyl Cyanoacetate	1.0648	20	A	2.50	25	A
Ethylcyclohexane	0.7879	20	A	0.843	20	A
Ethylene Carbonate	1.3208	40	A			
2,2'-(Ethylenedioxy)diethanol	1.1235	20	A	49.0	20	A
Ethylenimine	0.832	25	A	0.418	25	A
Ethyl Formate	0.9160	20	A	0.419	15	A
2-Ethyl-1-hexanol	0.8332	20	A	9.8	20	A
2-Ethylhexyl Acetate	0.8718	20	A	1.5	20	A
Ethyl Lactate	1.0299	25	A	2.44	25	A
Ethyl 3-Methylbutanoate	0.8657	20	A			
Ethyl Propanoate	0.8957	15	A	0.564	15	A
Ethyl Salicylate	1.1362	20	A	1.772	45	A
Fluorobenzene	1.0240	20	A	0.620	15	A
o-Fluorotoluene	1.0014	17	A	0.680	20	A
m-Fluorotoluene	0.9974	20	A	0.608	20	A
p-Fluorotoluene	0.9975	20	A	0.622	20	A
Formamide	1.1334	20	A	3.764	20	A
Formic Acid	1.2141	25	A	1.966	25	A
2-Furaldehyde	1.1616	20	A	1.49	25	A
Furan (Furfuran)	0.9378	20	A	0.380	20	A
Furfuryl Alcohol	1.1285	20	A	4.62	25	A
Glycerol	1.2582	25	A	945.	25	A
Glyceryl Triacetate	1.160	20	C	17.4	20	C
Heptane	0.6795	25	A	0.397	25	A
1-Heptanol	0.8223	20	A			
2-Heptanol	0.8139	25	A	5.06	25	A
1-Heptene	0.6970	20	A	0.35	20	A
Hexadecane	0.7733	20	B	3.34	20	B
1-Hexadecanol	1.4355	60	A			
Hexafluorobenzene	1.6182	20	A			
Hexamethylphosphoric Triamide	1.027	20	A	3.47	20	A
Hexane	0.6594	20	A	0.313	20	A
Hexanenitrile	0.8052	20	A	1.041	25	A
Hexanoic Acid	0.9230	25	A	2.814	25	A
1-Hexanol	0.8162	25	A	4.592	25	A
2-Hexanol	0.8144	20	A			
3-Hexanol	0.8185	20	A			
1-Hexene	0.6732	20	A	0.26	20	A
4-Hydroxy-4-methyl-2-pentanone	0.9341	25	A	2.9	20	A
Hydrazine				0.97	20	B
Iodobenzene	1.9307	20	A	1.774	17	A
Iodoethane	1.9358	20	A	0.617	15	A
Iodomethane	2.2790	20	A	0.518	15	A
1-Iodopropane	1.7489	20	A	0.837	15	A

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
2-Iodopropane	1.7025	20	A	0.732	15	A
Isobutylamine	0.7346	20	A	0.553	25	A
Isobutyronitrile	0.7656	25	A	0.456	30	A
Isopropyl Acetate	0.8718	20	A	0.569	20	A
Isopropylamine	0.6875	20	A	0.36	25	A
Isopropylbenzene	0.8618	20	A	0.791	20	A
Isoquinoline	1.0986	25	A			
Lactic Acid	1.2060	25	A	40.33	25	A
Methacrylic Acid	1.0153	20	A			
Methacrylonitrile	0.8001	20	A	0.392	20	A
Methanol	0.7866	25	A	0.544	25	A
Methoxybenzene	0.9893	25	A	0.789	30	A
2-Methoxyethanol	0.9646	20	A	1.72	20	A
2-(2-Methoxyethoxy)ethanol	1.0167	25	A	3.48	25	A
2-Methoxyethyl Acetate	1.0049	20	A			
N-Methylacetamide	0.9460	35	A	3.23	35	A
Methyl Acetate	0.9273	25	A	0.362	25	A
Methyl Acetoacetate	1.0747	20	A	1.704	20	A
Methyl Acrylate	0.9535	20	A	1.398	20	A
Methyl Benzoate	1.0933	15	A	2.298	15	A
2-Methylbutane	0.6197	20	A	0.225	20	A
4-Methylbutanenitrile	0.8035	20	A	0.980	20	A
2-Methylbutanoic Aetate	0.8719	20	A	0.872	20	A
3-Methylbutanoic Acid	0.9308	15	A	2.731	15	A
2-Methyl-1-butanol	0.8190	20	A	5.50	20	A
3-Methyl-1-butanol	0.8103	20	A	4.81	15	A
2-Methyl-2-butanol	0.8090	20	A	5.48	15	A
3-Methyl-2-butanol	0.8179	20	A	3.51	25	A
3-Methylbutyl Acetate	0.8664	25	A	0.790	25	A
Methyl Butyrate	0.8984	25	A	0.543	25	A
Methyl Cyanoacetate	1.1225	25	A	2.793	20	A
Methylcylcohexane	0.7694	20	A	0.734	20	A
cis-2-Methylcyclohexanol	0.9254	20	A	18.08	25	A
trans-2-Methylcyclohexanol	0.9247	20	A	37.13	25	A
cis-3-Methylcylohexanol	0.9168	20	A	19.7	25	A
trans-3-Methylcylohexanol	0.9214	20	A	25.1	25	A
cis-4-Methylcyclohexanol	0.9122	20	A	0.247	25	A
trans-4-Methylcyclohexanol	0.9080	25	A	0.385	25	A
Methylcyclopentane	0.7486	20	A	0.507	20	A
N-Methylformamide	0.9988	25	A	1.65	25	A
Methyl Formate	0.9742	20	A	0.328	25	A
2-Methylhexane	0.6786	20	A	0.378	20	A
3-Methylhexane	0.6871	20	A	0.372	20	A
Methyl Methacrylate	0.9433	20	A	0.632	20	A
Methyl Oleate	0.8702	20	A	4.88	30	A
2-Methylpentane	0.6532	20	A	0.310	20	A
3-Methylpentane	0.6643	20	A	0.307	25	A
2-Methyl-1-pentanol	0.8242	20	A			
3-Methyl-1-pentanol	0.8237	20	A			
4-Methyl-1-pentanol	0.8130	20	A			
2-Methyl-2-pentanol	0.8136	20	A			
3-Methyl-2-pentanol	0.8291	20	A			
4-Methyl-2-pentanol	0.8076	20	A	4.074	25	A
2-Methyl-3-pentanol	0.8239	20	A			
3-Metnyl-3-pentanol	0.8291	20	A			
4-Methyl-2-pentanone	0.8006	20	A	0.542	25	A
2-Methylpropanamine	0.7346	20	A			
2-Methylpropanoic Acid	0.9682	20	A	1.213	25	A
2-Methyl-1-propanol	0.7978	25	A	3.91	25	A
2-Methyl-2-propanol	0.7812	25	A	3.316	30	A
N-Methylpropionamide	0.9305	25	A	5.215	25	A
Methyl Propionate	0.9221	15	A	0.477	15	A
1-Methylpropyl Acetate	0.8720	20	A			

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
2-Methylpropyl Acetate	0.8745	20	A	0.697	20	A
2-Methylpropyl Formate	0.8854	20	A	0.680	20	A
2-Methylpyridine	0.9444	20	A	0.805	20	A
3-Methylpyridine	0.9566	20	A			
4-Methylpyridine	0.9548	20	A			
1-Methyl-2-pyrrolidinone	1.0279	25	A	1.666	25	A
Methyl Salicylate	1.1831	20	A			
Morpholine	1.0050	15	A	38.27	15	A
Napthalene	0.9752	85	A	0.780	99	A
o-Nitroanisole	1.2408	25	A			
Nitrobenzene	1.2033	20	A	1.634	20	A
Nitroethane	1.0382	25	A	0.661	25	A
Nitromethane	1.1312	25	A	0.595	30	A
1-Nitro-2-methoxybenzene	1.2527	20	A			
1-Nitropropane	0.9955	25	A	0.798	25	A
2-Nitropropane	0.9821	25	A	0.750	25	A
o-Nitrotoluene	1.1629	20	B	2.37	20	B
m-Nitrotoluene	1.1571	20	B	2.33	20	B
p-Nitrotoluene	1.1038	20	B	1.20	60	B
Nonane	0.7176	20	A	0.7160	20	A
1-Nonanol	0.8280	20	A			
1-Nonene	0.7922	20	A	0.620	20	A
1-Octadecanol	0.8123	20	A			
Octane	0.7025	20	A	0.546	20	A
Octanenitrile	0.8059	30	A	1.356	30	A
Octanoic Acid	0.9106	20	A	5.828	20	A
1-Octanol	0.8258	20	A	6.125	30	A
2-Octanol	0.8207	20	A			
3-Octanol	0.8216	20	A			
4-Octanol	0.8192	20	A			
1-Octene	0.7149	20	A	0.470	20	A
Oil, Castor	0.96	25	E	986.	20	B
Oil, Cottonseed	0.922	20	E	70.4	20	B
Oil, Linseed	0.932	20	E	33.1	30	B
Oil, Light Machine	0.87	20	F	113.8	16	B
Oil, Heavy Machine	0.89	20	F	660.6	16	B
Oil, Olive	0.915	20	E	84.0	20	B
Oil, Soya Bean	0.922	20	E	69.3	20	B
Oleic Acid	0.8906	20	A	38.80	20	A
2,2'-Oxybis(chloroethane)	1.2192	20	A	2.41	20	A
2,2-Oxydiethanol	1.1167	20	A	35.7	20	A
Pentachloroethane	1.6881	15	A	2.751	15	A
Pentadecane	0.7685	20	B	2.81	22	B
cis-1,3-Pentadiene	0.6859	25	A			
trans-1,3-Pentadiene	0.6710	25	A			
2,3-Pentadiene	0.6900	25	A			
Pentane	0.6214	25	A	0.225	25	A
2,4-Pentanedione	0.9721	25	A			
Pentanenitrile	0.8035	15	A	0.779	15	A
1-Pentanoic Acid	0.9392	20	A	2.359	15	A
1-Pentanol	0.8112	25	A	3.347	25	A
2-Pentanol	0.8053	25	A	2.780	30	A
3-Pentanol	0.8160	25	A	3.306	30	A
2-Pentanone	0.8095	20	A			
3-Pentanone	0.8144	20	A	0.478	20	A
1-Pentene	0.6405	20	A	0.24	0	A
cis-2-Pentene	0.6556	20	A			
trans-2-Pentene	0.6482	20	A			
Pentyl Acetate	0.8753	20	A	0.924	20	A
Phenol	1.0533	46	A	4.076	46	A
Phenylacetonitrile	1.0125	25	A	1.93	25	A
D-Pinene	0.8600	20	A	1.61	25	A
L-Pinene	0.8590	20	A	1.41	25	A

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
Piperidine	0.8613	20	A	1.362	25	A
1-Propanal	0.7970	20	A	0.317	20	A
1,2-Propanediol	1.0364	20	A	56.0	20	A
1,3-Propanediol	1.0538	20	A	46.6	20	A
Propanenitrile	0.7911	20	A	0.624	15	A
1-Propanol	0.7995	25	A	2.004	25	A
2-Propanol	0.7813	25	A	1.765	30	A
2-Propen-1-ol [Allyl Alcohol]	0.8551	15	A	1.486	15	A
Propionic Acid	0.9934	20	A	1.175	15	A
Propionic Anhydride	1.0110	20	A	1.144	20	A
Propionitrile	0.7818	20	A	0.454	15	A
Propyl Acetate	0.8883	20	A	0.585	20	A
Propylamine	0.7173	20	A	0.353	25	A
Propyl Benzoate	1.0232	20	A			
Propylene Oxide	0.8287	20	A	0.327	20	A
Propyl Formate	0.9006	20	A	0.574	20	A
2-Propyn-1-ol	0.9478	20	A	1.68	20	A
1-Propynyl Acetate	0.9982	20	A			
Pyridine	0.9832	20	A	0.952	20	A
Pyrrole	0.9699	20	A	1.352	20	A
2-Pyrrolidinone	1.107	25	A	13.3	25	A
Quinoline	1.0977	15	A	4.354	15	A
Salicyaldehyde	1.1574	20	A	2.90	20	A
Succinonitrile	0.9867	60	A	2.591	60	A
Sulfolane	1.2614	30	A	10.286	30	A
Styrene	0.9060	20	A	0.751	20	A
1,1,2,2-Tetrabromoethane	2.9640	20	A	9.79	20	A
1,1,2,2Tetrachlorodifluoroethane	1.6447	25	A	1.21	25	A
1,1,2,2-Tetrachloroethane	1.6026	15	A	1.844	15	A
Tetrachloroethene (PERC)	1.6311	15	A	1.932	15	A
Tetrachloromethane [Carbon Tet.]	1.5842	20	A	0.969	20	B
Tetradecane	0.7628	20	B	2.18	20	B
1-Tetradecanol	0.8151	50	A			
Tetrahydrofuran	0.8889	20	A	0.55	20	A
Tetrahydrofurfuryl Alcohol	1.0524	20	A	6.24	20	A
1,2,3,4-Tetrahydronapthalene	0.9702	20	A	2.202	20	A
Tetrahydropyran	0.8772	25	A	0.764	25	A
Tetrahydrothiophene	0.9938	25	A	0.971	25	A
1,1,2,2-Tetramethylurea	0.9654	25	A			
Tetranitromethane	1.6372	21	A			
2-Thiabutane	0.8422	20	A	0.373	20	A
Thiacyclobutane	1.0200	20	A	0.638	20	A
Thiacyclohexane	0.9861	20	A			
Thiacyclopentane	0.9987	20	A	1.042	20	A
2-Thiapentane	0.8424	20	A			
3-Thiapentane	0.8363	20	A	0.440	20	A
2-Thiapropane	0.8483	20	A	0.289	20	A
Thiophene	1.0649	20	A	0.654	20	A
Toluene	0.8623	25	A	0.552	25	A
o-Toluidine	1.0028	15	A	5.195	15	A
m-Toluidine	0.9930	15	A	4.418	15	A
p-Toluidine	0.9538	60	A	1.557	60	A
Tribromomethane (Bromoform)	2.9035	15	A	2.152	15	A
Tri-n-butyl Borate	0.8580	20	A	1.776	20	A
Tri-n-butyl Phosphate	0.9760	25	A	3.39	25	A
Trichloroacetonitrile	1.4403	25	A			
1,1,1-Trichloroethane	1.3492	20	A	0.903	15	A
1,1,2-Trichloroethane	1.4424	20	A	0.119	20	A
Trichloroethene (TCE)	1.4679	20	A	0.566	20	A
Trichloromethane [Chloroform]	1.4985	15	A	0.596	15	A
1,2,3-Trichloropropane	1.3880	20	A			
Tricresyl Phosphate	1.173	20	C	80.0	20	C
Tridecane	0.7563	20	A	18.834	20	A

Table A-3. Density and Viscosity Data for Selected Chemicals.

Chemical	Density (g/cm3)	Temp. C.	Ref.	Absolute Viscosity (cp)	Temp. C.	Ref.
1-Tridecene	0.7653	20	A			
Triethanolamine	1.1196	25	A	613.6	25	A
Triethylamine	0.7281	20	A	0.394	15	A
Trifluoroacetic Acid	1.4890	20	A	0.926	20	A
1,2,3-Trimethylbenzene	0.8944	20	A			
1,2,4-Trimethylbenzene	0.8758	20	A	0.895	15	A
1,3,5-Trimethylbenzene	0.8652	20	A	1.154	20	A
2,2,3-Trimethylbutane	0.6901	20	A	0.579	20	A
cis-1,3,5-Trimethylcyclohexane	0.7705	20	A	0.632	20	A
trans-1,3,5-Trimethylcyclohexane	0.7789	20	A	0.714	20	A
2,2,3-Trimethylpentane	0.7160	20	A	0.598	20	A
2,2,4-Trimethylpentane	0.6919	20	A	0.504	20	A
Turpentine				1.487	20	B
Undecane	0.7402	20	A	11.855	20	A
1-Undecanol	0.8324	20	A			
Vinyl Acetate	0.9312	20	A	23.95	20	A
o-Xylene	0.8802	20	A	0.809	20	A
m-Xylene	0.8642	20	A	0.617	20	A
p-Xylene	0.8611	20	A	0.644	20	A

References:

A Lange's Handbook of Chemistry, 1987, McGraw-Hill, New York.

B Weast, R. C., (ed.), 1972, Handbook of Chemistry and Physics, 53rd Edition, CRC Publishing Co., Cleveland, Ohio.

C Ashland Chemicals, 1985-1986, Product Catalog.

D Schwille, F., 1988, Dense Chlorinated Solvents in Porous and Fractured Media, Lewis Publishers, Chelsea, MI.

E U.S. Coast Guard, 1978, CHRIS Hazardous Chemical Data.

F Chevron, 1988, Product Salesfax Digest.

Appendix B - Pump-and-Treat Applications

TABLE B-1. SUMMARY OF PUMP-AND-TREAT APPLICATIONS

Site Name & State	GW Region	Aquifer Properties	Major Contaminants	NAPL	Remediation Design	Treatment	Monitoring Capabilities	Effectiveness/ Limitations
Des Moines, IA [Well monitored]	Glaciated Central Region	Highly permeable, unconfined sand and gravel aquifer. Laterally extensive. SS, SH, and LS bedrock aquifers below.	TCE and byproducts: trans-1,2-DCE, VC. Max. conc. TCE= 8,967 ppb	No	7 recovery wells, total pumpage = 1300 gpm.	Air stripper	60 wells & piez., monthly WQ from 36 wells for 34 VOCs plus WLs.	• Effective zone of capture developed within 6 months. • Lack of fine grained seds. in aquifer favors extraction. • Significant decline in concentrations. • Vadose zone contamination may cause lengthy remediation
Site A, FL [Small plume]	Southeast Coastal Plain	Biscayne aquifer, sole source. Highly permeable sand and limestone, flat water table.	Mostly limited to upper portion of aquifer. Benzene, CB, 1-4-dichlorobenzene trans-1,2-DCE, VC	No	1 recovery well, total pumpage = 30-50 gpm, screened 15 to 25 ft. bls.	Air stripper, discharge to city sewer system	14 wells sampled 6 times over 6 months	• Chemical concentrations in most monitor wells have been reduced significantly. • Overoptimistically designed 25 to 60 day cleanup not obtained, but appears to be making good progress.
DuPont Mobile Plant, AL	Atlantic and Gulf Coastal Plain	Unit A clay, unit B sand, and unit C clay. Unit B sand is now unconfined due to pumping.	PCAP, CBT	No	Initially 2 wells at 62.5 gpm each. 2 wells added later to improve capture effectiveness. 4 wells in line.	Onsite industrial bio-treatment, discharged to Mobile River.	Approx. 50 wells, but limited chemical data.	• 4 years of extraction have reduced contamination extent and levels in upper aquifer. • Data not available to assess deeper aquifer.
Fairchild Semiconductor Corp., CA [Extensive remediation]	Alluvial Basin	300-400 ft. of Quaternary alluvium. Multiaquifer system. Aquifers A-D are sand and gravel, separated by silt and silty clay.	Xylene, Acetone, TCE, IPA, Freon-113, Max conc. in aquifer A: Acetone = 99,000,000 ppb, Xylene = 76,000,000 ppb. Chemicals have migrated laterally and vertically.	Concn. exceed solubility	Included soil removal, slurry wall construction, aquifer flushing, in-situ soil aeration, and pump and treat. 36 recovery wells phased in. Total pumpage started at 1,260 gpm from 1 well, peaked at 9,200 gpm, and has since been reduced to 2,100 gpm.	Air stripping or hauled offsite. Discharge to Canoas Creek via San Jose storm sewer system. GAC used if needed.	40 recovery wells sampled biweekly. 84 monitor wells sampled sporadically.	• In operation for 7 yrs. • Hydraulically successful. • Chemical concentrations reduced 3 orders of magnitude in upper 3 aquifers. • 90,000 pounds of solvents removed.

Site Name & State	GW Region	Aquifer Properties	Major Contaminants	NAPL	Remediation Design	Treatment	Monitoring Capabilities	Effectiveness/ Limitations
Ponders Corner, WA	Alluvial Basin	Dominantly glacial sand and gravel. Some perched zones. Strong downward vertical gradient, fairly heterogeneous. Groundwater flows affected by septic tank discharge and production well pumping.	Dry cleaning wastes: no PCE, TCE, 1,2-T-DCE	No	Since 1984, 2 production wells pumped a total of 2,000 gpm. 1988, vapor extraction in vadose zone initiated.	Air stripping.	42 monitor wells. Fairly limited sampling program. Most chemical data from pumping wells.	· Periodic shutdown of some production wells has allowed main plume to migrate beyond zone of capture. · Chemicals adsorb to low permeability till, slow releases. · Overall, definite reduction of contaminants at well head.
IBM-Dayton, NJ [Long remediation history]	Nonglaciated Central Region	Sand with clay layers over relatively impermeable Brunswick shale bedrock.	TCA, PCE. Max conc. TCA = 9590 ppb.	Yes DNAPL	13 shallow wells, 1 deep well.	Air stripping and reapplication via spray irrigation and injection wells.	Nearly 100 monitoring wells. Long history.	· 1978 through 1984 remediation deemed successful. · Continued monitoring showed chemical concentration increased after extraction shutdown. · Additional pump and treat planned for plume containment.
Gen. Rad. Corp., MA	Northeast and Superior Uplands	Stratified, permeable glacial sand and gravel over relatively impermeable till and bedrock.	TCE and by products: 1,1-DCA, 1-1 DCE, MC, trans-1,2-DCE, 1,1,1-TCA, VC, tetrachloroethylene	No	2 wells, each 15 gpm or greater. Shutdown 25% of year (winter).	Air stripping	16 monitor wells, sampled quarterly.	· Under review. · Consultants suggest 40% reduction in plume contaminants.
Nichols Eng. and Research Corp., NJ	Nonglaciated Central Region	Weathered/fractured shale; near vertical fractures.	Carbontet., chloroform, PCE	DNAPL suspected but not found	Phased approach. Initially 1 well at 60-65 gpm. 1/89, 2 additional wells on line. Total extraction still only 70 gpm (discharge permit restriction).	Direct discharge to HMVA.	4 wells sampled monthly. 8 other wells sampled sporadically.	· Carbontet. conc. reduced 80 to 90% in some wells. · Rate of chemical removal has dropped significantly. · Significant quantities of carbontet. suspected in vadose zone. · May add intermittent pumping, soil vapor extraction, or artificial recharge to improve recovery in vadose zone.

Site Name & State	GW Region	Aquifer Properties	Major Contaminants	NAPL	Remediation Design	Treatment	Monitoring Capabilities	Effectiveness/ Limitations
Verona Well Field, MI	Glaciated Central Region	Glacial outwash (sand. gravel and some clay locally) overlying a fractured, permeable sandstone aquifer.	1,1-DCA, 1,2-DCA, 1,1,1-TCA, 1,2-DCE, 1,1-DCE, TCE, PCE. Total VOCs > 100,000 ppb.	Yes, LNAPL up to 6 in. thick mostly Tour-ene based	3-phase approach. To protect wellfield, 5 existing production wells pumped "at minimum." Onsite, 9 water-table recovery wells, total pumpage = 400 gpm. 23 PVC wells for vapor extraction.	Carbon pre-treatment (if nec) and air stripping (vapor-phase carbon ad-sorption, if needed). Discharge to Battle Cr. Riv.	Water quality from 5 extraction wells.	· Effectively blocked migration. · Residual LNAPL slows cleanup. · Vapor extraction has accelerated cleanup.
IBM General Products Div., CA [Complex site]	Alluvial Basin	Alluvial sand and gravel, with silt and clay layers. Multiple aquifer system (aquifers A-E). Heterogeneous.	Freon, TCA, DCE, TCE. Complex contaminant distribution.	Yes, Prod. not ex-plained.	Over 23,000 cubic yds. of soil and 65 buried storage tanks removed. 3 separate extraction systems (source area, boundary system, offsite system). 30 total extraction wells. Complex pumping schedule.	Not specified.	Over 350 monitoring wells. Most wells sampled monthly or quarterly for selected parameters. Over 25,000 groundwater samples coll.	· Reduced contami-nation concentrations onsite in shallow aquifer but little change in other areas. · Over 7,600 pounds of solvent removed by extraction system from 1983-1987.
Emerson Electric Co., FL [Only site designated as "clean"]	Southeast Coastal Plains	Unconfined sand. Relatively homogeneous.	Acetone, MEK, MIBK, Toluene, DCE, DCA, TCE, TCA, Benzene, Chromium	No	5 surficial wells, total pumpage = 30 gpm.	Directly to municipal sanitary sewer network.	Composite and individual water quality samples from recovery wells. Conc. data from moni-toring wells not reported.	· Projected cleanup of 7 months not obtained. · Most contaminants in recovery wells reduced to BDL after 20-22 months. · Site removed from · State Action Site listing on 1/89. · Inadequate monitoring.
General Mills, Inc., MN	Glaciated Central Region	Glacial drift aquifer underlain by till and several bedrock (SH, SS, LS) aquifer.	TCE, PCE, TCA, BTX and organic degrada-tion byproducts.	No effort to detect	5 recovery wells in water-table aquifer, total pumpage = 370 gpm. 1 recovery well in deep aquifer at 20-30 gpm.	3 wells: air stripping then discharge to storm sewer. 3 wells: discharge directly to storm sewer.	Not clear.	· Significant concentra-tion declines in 1988 but drought year. · Hydraulic gradients (particularly vertical) not satisfactorily con-trolled; part of plume is being missed. · It is unlikely cleanup goals will be achieved: shallow < 270 ppb TCE, deep < 27 ppb TCE.

Site Name & State	GW Region	Aquifer Properties	Major Contaminants	NAPL	Remediation Design	Treatment	Monitoring Capabilities	Effectiveness/ Limitations
Harris Corp., FL [Too many consultants]	Southeast Coastal Plain	Two sand aquifers separated by a leaky clay aquitard. Heterogeneous.	T-1,2-DCE, TCE, VC, MC, CB. Other volatile and nonvolatile organics are present.	No	4 offsite production wells pumped. 10 points later replaced by 2 rec. wells. Well point "problems." 4 deep barrier wells: 2 shallow, 3 shallow, 3 deep - 25 gpm each. 3 deep - 50 gpm, tot. pumpage = 275 gpm.	Air stripper then discharge to deep well injection.	Not clear	- Well head protection objective achieved better than plume containment. - Ineffective capturing shallow plume migration downgradient.
Amphenol Corp., NY [Relatively low initial VOC conc.]	Glaciated Central Region	200 ft. alluvial sequence. Sand and gravel with some silt and clay. Relatively permeable, heterogeneous.	VOCs, mostly TCE and chloroform. Max. VOC concentration in well = 329 ppb.	No	2 recovery wells: shallow zone - 57 gpm, deep zone - 150 gpm.	Air stripping, discharge to Susquehanna River.	Sampled 12-17 wells quarterly.	. Groundwater divide successfully developed between plume and production wells. - VOC concentrations have been reduced during 1 1\2 years operation and fluctuate much less. - Seasonal recharge and river fluctuations strongly influence flow patterns and may temporarily modify desired capture zones. - Remediations status is on schedule, anticipate 5-10 years remediation.
A/M Area, SRP, SC	Atlantic and Gulf Coastal Plain	Sand, silt, clay. Heterogeneous. Downward vertical flow at site.	TCE, PCE, TCA	No	11 recovery wells, total pumpage = 395 gpm, limited by air stripper discharge pump.	Air stripping, discharge to A-104 outfall.	"165 monitoring wells sampled in 1988."	. Downward migration reduced. . Only very slight reduction in size and concentration of TCE plume over 3 years remediation. . Expected to take longer than the projected 30 years to remove 99% of initial contaminants.

Site Name & State	GW Region	Aquifer Properties	Major Contaminants	NAPL	Remediation Design	Treatment	Monitoring Capabilities	Effectiveness/ Limitations
Utah Power and Light Pole Treatment Yard, ID	Columbia Lava Plateau	Individual lava flows separated by sediments. Vertical fractures in lava. Very heterogeneous.	Creosote - mostly PAHs. Low solubility, low mobility.	Yes DNAPL	Soil excavated. Two stage approach. 6-month pilot program. 3 wells in upper aquifer, 2 wells in lower aquifer, total pumpage = 25 gpm. Many problems with high concentrations (slugs) of NAPL extraction: - reduced flow rate - incompatible with PVC - clogging. Second 6-mo. pilot program went well into full scale. 7 wells in upper aquifer, total pumpage = 46 gpm, 7 wells in lower aquifer, total pumpage = 145 gpm.	"Treated" and released to sewer system or Snake River.	Not clear.	- Flow pattern has successfully been altered, both areal and vertical. - NAPL is being recovered. - Difficult to determine overall success due to chemical fluctuations.
Black and Decker, NY	Glaciated Central Region	Thin till layer overlying fractured sandstone and shale bedrock.	TCE, TCA, and byproducts DCE and VC.	No	Initially tried one bedrock recovery well at 3.4 gpm. Inadequate rate. Used explosives to create fracture zone perpendicular to flow. Pumping one recovery well in new fracture zone at 18.5 gpm.	Not clear.	15 monitor wells sampled for VOCs. 2 monitor wells in new fracture zone.	- No significant changes in VOCs observed.
Olin Chemicals DOE Rem Facility, KY	Non-glaciated Central Region	Unconsolidated, heterogeneous but highly permeable, glacio-fluvial sediments overlying low permeability limestone bedrock.	Dichloroethyl ether (DCEE) Dichloroisopropyl ether (DCIPE) Highly mobile.	No	3 recovery wells between plume and Ohio River, total pumpage = 3000-5000 gpm.	Used as process water, biologically treated at onsite activated-sludge wastewater treatment plant and discharged through state PDES.	Semiannual sampling of several monitor wells.	- No operational problems noted except 80-90% of extracted water is induced river recharge. - In general, concentrations have declined in monitoring wells in 4 years. [DCIPE] 1984/1270 ppb 1988/300 ppb - 5 new recovery wells planned for 1989.